U.S. DEPARTMENT OF COMMERCE
National Technical Information Service
PB80-157282

Capital and Operating Costs of Selected Air Pollution Control Systems

GARD, Inc, Niles, IL

Prepared for

Environmental Protection Agency, Research Triangle Park, NC

Dec 78

PB80-157282

EPA 450/5-80-002

CAPITAL
AND OPERATING COSTS
OF SELECTED AIR POLLUTION
CONTROL SYSTEMS

by

R. B. Neveril

GARD, INC.
7449 North Natchez Avenue
Niles, Illinois 60648

Contract No. 68-02-2899

EPA Project Officer: Frank Bunyard/William Vatavuk

Prepared for

ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Waste Management
Office of Air Quality Planning and Standards
Research Triangle Park, North Carolina 27711

December, 1978

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.
EPA 450/5-80-002

2.

3. RECIPIENT'S ACCESSION NO.
PB80-157282

4. TITLE AND SUBTITLE
Capital and Operating Costs of Selected Air Pollution Control Systems

5. REPORT DATE
December, 1978

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
R. B. Neveril

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
GARD, INC.
7449 North Natchez Avenue
Niles, Illinois 60648

10. PROGRAM ELEMENT NO.

11. CONTRACT/GRANT NO.
EPA 68-02-2899

12. SPONSORING AGENCY NAME AND ADDRESS
Environmental Protection Agency
Office of Air and Waste Management
Office of Air Quality Planning and Standards
Research Triangle Park, North Carolina 27711

13. TYPE OF REPORT AND PERIOD COVERED
Final

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

and

16. ABSTRACT

The prupose of this manual is to provide capital and operating costs for air pollution control systems. Capital costs are provided for component equipments, such as ductwork, dampers, heat exchangers, mechanical collectors, fans, motors, stacks, cooling towers, pumps, and dust removal equipment. Eight types of control devices are included: (1) high voltage electrostatic precipitators, (2) venturi scrubbers, (3) fabric filters, (4) thermal and catalytic incinerators, (5) adsorbers, (6) absorbers, (7) refrigeration, (8) flares. Operating and maintenance costs are provided for complete systems. A discussion of the control devices and factors affecting costs is included, along with design parameters for 52 industries. In preparing this manual, the main objective was to "break-out" the individual component costs so that realistic system cost estimates can be determined for the design peculiarities of any specific application. Accuracy of the cost data presented is generally ± 20%.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Industrial Emission Sources Costs Manual Fabric Filters, Absorbers, Flares, Scrubbers, Refrigeration Electrostatic Precipitators Adsorbers, Incinerators	Cost Estimation Techniques Capital Costs Annualized Costs Air Pollution Control Systems	

18. DISTRIBUTION STATEMENT Unlimited	19. SECURITY CLASS (This Report) Unclassified	21. NO. OF PAGES
	20. SECURITY CLASS (This page) Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

NOTICE

This report was furnished to the Environmental Protection Agency by GARD, INC., Niles, Illinois in fulfillment of Contract No. 68-02-2899. The contents of this report are reproduced herein as received from the contractor. The opinions, findings, and conclusions expressed are those of the author and not necessarily those of the Environmental Protection Agency. Mention of company or product names is not to be considered as an endorsement by the Environmental Protection Agency.

TABLE OF CONTENTS

Section		Page
LIST OF TABLES
LIST OF FIGURES
1	INTRODUCTION	1-1
1.1 Purpose of Manual	1-1
1.2 Organization of Manual	1-2
2	APPLICATION TO INDUSTRY	2-1
3	COST ESTIMATING PROCEDURES	3-1
3.1 Capital Costs	3-2
3.1.1 Purchased Equipment Costs	3-5
3.1.2 Installation Costs	3-9
3.2 Annualized Costs	3-10
3.2.1 Direct Operating Costs	3-13
3.2.2 Indirect Operating Costs	3-18
4	AUXILIARY EQUIPMENT	4-1
4.1 Capture Hoods	4-2
4.2 Ducting	4-15
4.3 Gas Conditioning	4-29
4.4 Pollutant Removal and Treatment (Dust)	4-44
4.5 Ancillary Equipment (cooling towers, pumps)	4-47
4.6 Fans	4-57
4.7 Stacks	4-67
5	CONTROL DEVICES	5-1
5.1 High Voltage Electrostatic Precipitators	5-1
5.2 Venturi Scrubbers	5-9
5.3 Fabric Filters	5-19
5.4 Thermal and Catalytic Incinerator Systems	5-31
5.5 Adsorbers	5-39
5.6 Absorbers	5-50
5.7 Refrigeration	5-65
5.8 Flares	5-72
6	SAMPLE COST ESTIMATES AND SYSTEM COST COMPARISON	6-1
7	UPDATING COSTS TO FUTURE TIME PERIODS	7-1
7.1 General	7-1
7.2 Equipment Cost Updating Procedures	7-6

APPENDIX A COMPOUND INTEREST FACTORS

APPENDIX B EQUIPMENT COST INDEXES

APPENDIX C GUIDE TO REFERENCES TO THE INDUSTRIES

APPENDIX D GUIDE TO ASSOCIATIONS FOR THE INDUSTRIES

APPENDIX E CONVERSION FACTORS TO SI MEASUREMENTS

LIST OF TABLES

TABLE NUMBER		PAGE NUMBER
2.1	INDUSTRY POLLUTANT SOURCES AND TYPICAL CONTROL DEVICES	2-4
2.2	DESIGN PARAMETERS FOR RESPECTIVE INDUSTRIES FOR HIGH EFFICIENCY PERFORMANCE	2-10
2.3	EFFICIENCY OF CARBON ADSORPTION AND LEL'S FOR COMMON POLLUTANTS	2-11
3.1	CAPITAL COSTING	3-3
3.2	COST ADJUSTMENTS	3-7
3.3	CAPITAL COST SUMMARY	3-11
3.4	BASIS FOR ESTIMATING ANNUALIZED COSTS	3-12
3.5	ESTIMATED LABOR HOURS PER SHIFT	3-14
3.6	GUIDELINES FOR PARTS AND EQUIPMENT LIFE	3-16
4.1	MINIMUM VELOCITIES AND VENTILATION RATES FOR LOW CANOPY HOODS	4-7
4.2	MATERIAL COSTS	4-14
4.3	REFRACTORY ESTIMATING COSTS	4-25
4.4	DEFINITIONS FOR COOLING TOWER	4-50
4.5	PRICE ADJUSTMENT FACTORS FOR WET-BULB TEMPERATURES	4-50
4.6	PRICE ADJUSTMENT FACTORS FOR APPROACH ΔT	4-50
4.7	MOTOR RPM SELECTION GUIDE	4-62
4.8	PRICING FACTORS FOR OTHER MOTOR TYPES	4-62
4.9	MOTOR TYPE SELECTION	4-62
4.10	FAN SIZING FACTORS: AIR DENSITY RATIOS	4-63
5.1	BAG PRICES	5-32
5.2	APPROXIMATE GUIDE TO ESTIMATE GROSS CLOTH AREA	5-32

LIST OF TABLES

TABLE NUMBER		PAGE NUMBER
5.3	TECHNICAL ASSUMPTIONS FOR ESTIMATION OF DIRECT OPERATING COSTS	5-48
5.4	MINIMUM SHELL THICKNESS AT AMBIENT TEMPERATURE	5-63
5.5	COST OF TOWER PACKING	5-63
5.6	ADDITIONAL COSTS FOR FABRICATOR'S ENGINEERING, PURCHASING, ADMINISTRATION AND PROFIT	5-64

LIST OF FIGURES

FIGURE NUMBER	TITLE	PAGE NUMBER
4-1	CONTROL SYSTEM FLOW CIRCUIT	4-3
4-2	LOW CANOPY HOODS FOR COLD PROCESSES	4-6
4-3	RECTANGULAR CANOPY HOOD PLATE AREA REQUIREMENTS VS. HOOD LENGTH AND L/W	4-10
4-4	CIRCULAR HOODS PLATE REQUIREMENTS	4-11
4-5	LABOR COST FOR FABRICATED 10 GA. CARBON STEEL RECTANGULAR CANOPY HOODS	4-12
4-6	LABOR COST FOR FABRICATED 10 GA. CARBON STEEL CIRCULAR CANOPY HOODS	4-13
4-7	CARBON STEEL STRAIGHT DUCT FABRICATION PRICE PER LINEAR FOOT VS. DUCT DIAMETER AND PLATE THICKNESS	4-19
4-8	STAINLESS STEEL STRAIGHT DUCT FABRICATION PRICE PER LINEAR FOOT VS. DUCT DIAMETER AND PLATE THICKNESS	4-20
4-9	WATER COOLED CARBON STEEL STRAIGHT DUCT FABRICATION PRICE PER FOOT VS. DUCT DIAMETER	4-21
4-10	CARBON STEEL ELBOW DUCT PRICE VS. DUCT DIAMETER AND PLATE THICKNESS	4-22
4-11	STAINLESS STEEL ELBOW DUCT PRICE VS. DUCT DIAMETER AND PLATE THICKNESS	4-23
4-12	CARBON STEEL EXPANSION JOINT COSTS VS. DUCT DIAMETER	4-24
4-13	CARBON STEEL RECTANGULAR DAMPER PRICES VS. AREA FOR L/W = 1.3	4-27
4-14	CARBON STEEL CIRCULAR DAMPER PRICES VS. DIAMETER	4-28
4-15	CAPACITY ESTIMATES FOR MECHANICAL COLLECTORS	4-31
4-16	CRITICAL PARTIAL SIZE ESTIMATES FOR MECHANICAL COLLECTORS	4-32
4-17	MECHANICAL COLLECTOR PRICES FOR CARBON STEEL CONSTRUCTION VS. INLET AREA	4-33

LIST OF FIGURES

FIGURE NUMBER	TITLE	PAGE NUMBER
4-18	MECHANICAL COLLECTOR PRICES FOR STAINLESS STEEL CONSTRUCTION VS. INLET AREA	4-34
4-19	MECHANICAL COLLECTOR SUPPORT PRICES VS. COLLECTOR INLET AREA	4-35
4-20	MECHANICAL COLLECTOR DUST HOPPER PRICES FOR CARBON & STAINLESS STEEL CONSTRUCTION VS. COLLECTOR INLET AREA	4-36
4-21	MECHANICAL COLLECTOR SCROLL OUTLET PRICES FOR CARBON & STAINLESS STEEL CONSTRUCTION VS. COLLECTOR INLET AREA	4-37
4-22	FABRICATED 40 FT HIGH "U" TUBE HEAT EXCHANGER PRICES WITH HOPPERS AND MANIFOLDS	4-39
4-23	SPRAY CHAMBER COST VS. INLET GAS NOLUME	4-41
4-24	QUENCHER COSTS VS. INLET GAS VOLUME	4-43
4-25	PRICES FOR FABRICATED CARBON STEEL DILUTION AIR PORTS VS. DIAMETER AND PLATE THICKNESS	4-45
4-26	PRICES FOR SCREW CONVEYORS VS. LENGTH AND DIAMETER	4-46
4-27	PRICES FOR INSTALLED COOLING TOWERS FOR UNITS OF CAPACITY ≤ 1000 TONS	4-48
4-28	PRICES FOR INSTALLED COOLING TOWER BASED ON WET-BULB TEMPERATURE = 82°F AND APPROACH = 10°F	4-49
4-29	CAST IRON, BRONZE FITTED, VERTICAL TUBINE WET SUMP PUMP PRICES FOR 3550 RPM	4-53
4-30	CAST IRON, BRONZE FITTED, VERTICAL TURBINE WET SUMP PUMP PRICES FOR 1750 RPM	4-54
4-31	CAST IRON, BRONZE FITTED, VERTICAL TURBINE WET SUMP PUMP PRICES FOR 1170 RPM	4-55
4-32	PUMP MOTOR HP VS. CAPACITY AND HEAD FOR VERTICAL TURBINE PUMPS	4-56
4-33	BACKWARDLY CURVED FAN PRICES VS. CLASS, CFM AND ΔP FOR ARRANGEMENT NO. 1	4-59

LIST OF FIGURES

FIGURE NUMBER	TITLE	PAGE NUMBER
4-34	BHP, FAN RPM AND MOTOR AND STARTER PRICES VS. ΔP AND CFM	4-61
4-35	FAN INLET AND OUTLET DAMPER PRICES AS A FUNCTION OF CFM AND ΔP	4-65
4-36	V-BELT DRIVE PRICES	4-66
4-37	RADIAL FAN PRICES VS. SCFM AND ΔP FOR ARRANGEMENT NO. 1	4-68
4-38	FAN RPM AND MOTOR BHP FOR RADIAL FANS	4-69
4-39	RADIAL TIP FAN PRICES	4-70
4-40	STARTER AND MOTOR PRICES FOR VENTURI SCRUBBER APPLICATIONS (HIGH PRESSURE, HIGH BHP)	4-71
4-41	FABRICATED CARBON STEEL STACK PRICE VS. STACK HEIGHT & DIAMETER FOR 1/4 INCH PLATE	4-73
4-42	FABRICATED CARBON STEEL STACK PRICE VS. STACK HEIGHT & DIAMETER FOR 5/16 & 3/8 INCH PLATE	4-74
4-43	PRICES FOR TALL STEEL STACKS, INSULATED AND LINED	4-75
5-1	ELECTROSTATIC PRECIPITATOR CONTROL SYSTEM	5-5
5-2	DRY TYPE ELECTROSTATIC PRECIPITATOR PURCHASE PRICES VS. PLATE AREA	5-7
5-3	VENTURI SCRUBBER CONTROL SYSTEMS	5-12
5-4	1/8 INCH THICK CARBON STEEL FABRICATED SCRUBBER PRICE VS. VOLUME	5-13
5-5	METAL THICKNESS REQUIRED VS. VOLUME AND DESIGN PRESSURE	5-14
5-6	PRICE ADJUSTMENT FACTORS VS. PLATE THICKNESS AND VOLUME	5-15
5-7	SCRUBBER INTERNAL SURFACE AREA AND SEPARATOR DIAMETER AND HEIGHT VS. WASTE INLET GAS VOLUME	5-16

LIST OF FIGIRES

FIGURE NUMBER	TITLE	PAGE NUMBER
5-8	INTERNAL GAS COOLER BUBBLE TRAY COST VS. SEPARATOR DIAMETER	5-17
5-9	FABRIC FILTER CONTROL SYSTEMS	5-25
5-10	INTERMITTENT, PRESSURE, MECHANICAL SHAKER BAGHOUSE VS. NET CLOTH AREA	5-26
5-11	CONTINUOUS, SUCTION OR PRESSURE, PULSE JET BAGHOUSE PRICES VS. NET CLOTH AREA	5-27
5-12	CONTINUOUS, PRESSURE, MECHANICAL SHAKER BAGHOUSE PRICES VS. NET CLOTH AREA	5-28
5-13	CONTINUOUS, PRESSURE, RESERVE AIR BAGHOUSE PRICES VS. NET CLOTH AREA	5-29
5-14	CUSTOM PRESSURE OR SUCTION BAGHOUSE PRICES VS. NET CLOTH AREA	5-30
5-15	PRICES FOR THERMAL INCINERATORS WITHOUT HEAT EXCHANGERS	5-36
5-16	PRICES FOR THERMAL INCINERATORS WITH PRIMARY HEAT EXCHANGER	5-37
5-17	CATALYTIC INCINERATOR PRICES	5-38
5-18	ADSORPTION ISOTHERM FOR TOLUENE	5-43
5-19	PRICES FOR PACKAGED STATIONARY BED CARBON ADSORPTION UNITS WITH STEAM REGENERATION	5-45
5-20	PRICES FOR CUSTOM CARBON ADSORPTION UNITS	5-46
5-21	FABRICATED COST OF CARBON STEEL VESSEL	5-58
5-22	SKIRT AND SUPPORT COSTS FOR CARBON STEEL VESSEL	5-59
5-23	COST OF NOZZLES	5-60
5-24	COST OF TRAY, SUPPORT PLATE OR DISTRIBUTOR	5-61
5-25	CASCADE REFRIGERATION SYSTEM FOR VAPOR RECOVERY	5-67
5-26	REFRIGERATION VAPOR RECOVERY UNITS	5-70
5-27	INSTALLED COST OF INDUSTRIAL VAPOR COMPRESSION REFRIGERATION SYSTEMS	5-73
5-28	COST OF ELEVATED FLARES	5-77
5-29	COST OF GROUND LEVEL FLARES	5-78

LIST OF FIGURES

FIGURE NUMBER	TITLE	PAGE NUMBER
6-1	FABRIC FILTER SYSTEM DESIGN	6-4
6-2	ELECTROSTATIC PRECIPITATOR SYSTEM DESIGN	6-12
6-3	VENTURI SCRUBBER SYSTEM DESIGN	6-17
7-1	CHEMICAL ENGINEERING PLANT COST INDEX	7-3

Section 1

INTRODUCTION

1.1 Purpose of Manual

One of the aims of the U.S. Environmental Protection Agency (EPA) is to provide guidelines and technical assistance to state and local regulatory agencies responsible for controlling air pollution. The purpose of this manual is to assist those agencies in estimating the cost of air pollution control systems for various manufacturers and processors who must comply with existing and future standards or codes. At present, literature is available which gives generalized cost data for control systems based on industry averages. However, there is a wide range of magnitude in the cost data due to the variety of installations. In some cases, the cost of the control device itself may only represent 25 percent of the total capital costs while in other cases, it may be as high as 90 percent. These differences can be attributed to the cost of auxiliary equipment, method of controlling the source (direct exhaust or canopy hood, etc.), physical location of control equipment with respect to the source, local code requirements, characteristics of gas stream, plant location, and many other influencing factors. In preparing this manual, the main objective was to identify the individual component costs so that realistic system cost estimates can be determined for any specific application based on the peculiarities of the system.

In addition to capital costs, methods for estimating the operating and maintenance costs are provided for each type of control system so that annualized costs can be estimated.

1.2 Organization of Manual

The cost estimating procedures and cost curves in this manual are provided for those systems utilizing the following control devices:

1) High voltage electrostatic precipitators
2) Venturi scrubbers
3) Fabric filters
4) Thermal and catalytic incinerators
5) Adsorbers
6) Absorbers
7) Refrigeration
8) Flares

In Section 2, a list of the design parameters for the various control devices is provided and crossreferenced to the applicable industries and pollutant sources that use these systems. Section 3 describes the procedures used in estimating the capital and annualized costs of these systems. A description of the operation and basic cost curves for these control devices and the auxiliary equipment required in a completely integrated pollution control system is presented in Sections 4 and 5. This description outlines the various design options available to the engineer and the impact these options have on the total system cost. These data represent equipment costs based on a reference date of December, 1977 and are estimated to be accurate to ± 20 percent, on a component basis, except where noted. In Section 6, an example is provided of a typical application which can be controlled by each one of three possible particulate control devices. However, the methods and procedures, demonstrated in the example, are applicable to all industries where the control of emissions uses one or more of these eight control systems. A method of extrapolating the costs to a future date is discussed in Section 7.

Section 2

APPLICATION TO INDUSTRY

None of these eight control systems can be applied universally throughout the various industries. For instance, adsorbers, absorbers and refrigeration are effective only with gaseous pollutants while thermal and catalytic incinerators require combustible particulates or vapors for proper operation. Noncombustible particulate-laden gas streams must be controlled by precipitators, scrubbers, or fabric filters. Precipitators and fabric filters are used solely for particulate collection while scrubbers may be used for both particulates and gases (when used as a contactor/absorber). The selection of a control system for a particular process, therefore, may be limited to only one or two types of control devices. Table 2.1 lists industries with typical sources of pollutants and applicable control devices that are used to control these emissions.

In some cases, a control device may be compatable with the process but not selected due to the particular plant location or cost of utilities. For instance, the potentially high cost of maintenance and repair for damage due to freezing with scrubber systems may preclude the use of these systems in some colder northern states. The high use of electrical power and utilities associated with venturi scrubbers would make these systems less attractive in areas where water is scarce or electrical power is costly. Combustion processes such as those that occur in flares and incinerators may present safety hazards in some areas.

Product recovery is possible with all of the control devices with the exception of flares and incinerators which chemically dispose of the pollutants. In many cases, the recovered product must be further treated to produce a reuseable item, particularly with scrubbers which may replace an air pollution problem with a water pollution problem if waste water treatment is not incorporated into the system.

Typical design parameters for the collection of particulates with fabric filters, venturi scrubbers, and precipitators are shown in Table 2.2. These represent the normal range of air-to-cloth ratios, venturi pressure drops, and drift velocities associated with those control systems used in the collection of particulate pollutants from industries listed.

For gaseous pollutants, the design parameters are specifically related to the physical and chemical characteristics of the pollutant and the concentration of the pollutant in the gas stream. In the adsorption process, the concentration of pollutants is generally below the lower explosive limit and gas streams are usually at atmospheric pressure where vapor pressures of pollutants are low. An adsorbent such as activated carbon is ideally suited for these conditions in controlling hydrocarbon emissions from spray booths, printing presses, and processes involving the evaporation of solvents. The design parameters for a carbon adsorber would therefore depend on the adsorption efficiencies of carbon. Table 2.3 lists the types of solvents and the lower explosive limit that might be expected in the exhaust gases from such sources. The adsorption efficiency listed for each solvent provides the engineer with the general range of adsorbent capacities required for sizing the control device at the specified concentrations.

The primary concept in designing an absorber is to provide the maximum contact between the gas or solute and the liquid solvents since the rate of mass transfer between the two is dependent on exposed surface. The design parameters will depend on both the solubility of the gas in the solvent and the inlet concentration. Once the constituents and operating conditions are defined, several different types of absorbers and some scrubbers, can be selected. Preliminary design data and operating parameters for these systems are found in Sections 4 and 5 and in references 88 and 146.

The chemical and physical properties of the pollutant are most important when refrigeration is used as a means of collection and removal. The vapor pressure/temperature relationship for hydrocarbons and other constituents typically found in commercial and industrial gas streams is provided in references 88, 146 and 147.

Appendix C is a crossreference of literature information applicable to each industry. Appendix D lists trade associations related to industries where additional information may be obtained.

Table 2.1 INDUSTRY POLLUTANT SOURCES AND TYPICAL CONTROL DEVICES[1]

INDUSTRY	SOURCE	CONTROL SYSTEM	CAPTURE DEVICE	TYPICAL GAS FLOW DESIGN RATE	TYPICAL GAS TEMPERATURE
Asphalt Roofing	1) Saturator and storage tanks	1) Scrubber, precipitator, afterburner	1) Canopy hood and direct exhaust	1) 10,000-20,000 cfm Per saturator hood handling a 36" wide roll at line speeds of up to 500 fpm	1) 80-300F
Basic Oxygen Furnaces	1) Basic oxygen furnace 2) Charging hood	1) Precipitator, scrubber, baghouse 2) Same as 1	1) Full-canopy hood 2) Canopy hood	1) Function of lance rate and hood design 2) 300 fpm hood face	1) 3500-4000F 2) 150-400F
Benzene Handling & Storage	1) Vents, storage tanks	1) Afterburners, adsorbers, refrigeration	1) Direct exhaust	1) As required	1) 70-100F
Brick Manufacturing	1) Tunnel kiln 2) Crusher, mill 3) Dryer 4) Periodic kiln	1) Scrubber, baghouse precipitator 2) Baghouse, scrubber 3) Same as 1 4) Same as 1	1) Direct exhaust 2) Canopy hood 3) Same as 1 4) Same as 1	1) Combustion air fan capacity 2) 250 fpm hood face 3) Same as 1 4) Same as 1	1) 200-600F 2) 70F mill 3) 250F 4) Same as 1
Castable Refractories	1) Electric arc 2) Crusher, mill 3) Dryer 4) Mold and shakeout	1) Baghouse, scrubber 2) Same as 1 3) Same as 1 4) Same as 1	1) Direct exhaust 2) Canopy hood 3) Direct exhaust 4) Canopy hood	1) Infilt. air 2) 250 fpm hood face 3) Fan capacity 4) Same as 2	1) 3000-4000F 2) 70F 3) 300F 4) 150F
Chemical Manufacturing Waste Disposal	1) Miscellaneous sources	1) Afterburners, flares	1) As required	1) As required	1) As required
Clay Refractories	1) Shuttle kiln 2) Calciner 3) Dryer 4) Crusher, mill	1) Baghouse, precipitator, scrubber 2) Same as 1 3) Same as 1 4) Baghouse, precipitator	1) Direct exhaust 2) Same as 1 3) Same as 1 4) Canopy hood	1) Fan capacity 2) Same as 1 3) Same as 1 4) 250 fpm hood face	1) 150-800F kiln 2) Same as 1 3) 250F 4) 70F
Coal-fired Boilers	1) Steam generator	1) Precipitator, scrubber, baghouse	1) Direct exhaust	1) Induced draft fan capacity	1) 300F-700F
Conical Incinerators	1) Incinerator	1) Scrubber	1) Direct exhaust	1) Combustion air rate	1) 400-700F
Cotton Ginning	1) Incinerator	1) Scrubber	1) Direct exhaust	1) Combustion air rate	1) 500-700F
Degreasing	1) Degreaser tank	1) Adsorber, refrigeration	1) Slot or canopy hood	1) 50 cfm/ft^2 open area	1) 70F

Table 2.1 (Continued)

INDUSTRY	SOURCE	CONTROL SYSTEM	CAPTURE DEVICE	TYPICAL GAS FLOW DESIGN RATE	TYPICAL GAS TEMPERATURE
Detergent Manufacturing	1) Spray dryer	1) Scrubber, baghouse	1) Direct exhaust	1) Fan capacity	1) 180-250F
Direct Firing of Meat	1) Smokehouse	1) Afterburners, electrical precipitators	1) Direct exhaust	1) 1-4 cfm/sf floor area	1) 120-150F
Distilled Whiskey Processing	1) Distillation process	1) Adsorbers, afterburners	1) As required	1) As required	1) As required
Dry Cleaning	1) Washer, extractor, tumbler	1) Adsorber	1) Direct exhaust	1) Fan capacity	1) 70F
Electric Arc Furnaces	1) Arc furnace 2) Charging and tapping	1) Baghouse, scrubber, precipitator 2) Same as 1	1) Direct exhaust, full/side draft hood 2) Canopy hood	1) Function of lance rate and hood design-up to 200,000 acfm 2) 250 fpm hood face	1) 3000F (direct exhaust) 2) 150F (canopy)
Feed Mills	1) Storage bins 2) Mills/grinders 3) Flash dryer 4) Conveyors	1) Baghouse, scrubber 2) Same as 1 3) Same as 1 4) Same as 1	1) Direct exhaust 2) Canopy hood 3) Direct exhaust 4) Canopy hood	1) 250 fpm canopy hood face velocity 2) Same as 1 3) Air heater flow rate (dryer) 4) Same as 1	1) 70F 2) 70F 3) 170-250F 4) 70F
Ferroalloy Plants a) HC Fe Mn b) 50% Fe Si c) HC Fe Cr	1) Submerged arc furnace (open) 2) Submerged arc furnace (closed) 3) Tap fume	1) Scrubber, baghouse, precipitator 2) Scrubber 3) Same collector or baghouse	1) Full or canopy hood 2) Direct exhaust 3) Canopy	1) 2500-5500 scfm/mw with scrubber 2) a) 220 scfm/mw b) 180 scfm/mw c) 190 scfm/mw 3) 200 cfm/ft^2	1) 400-500F open arc 2) 1000-1200F closed arc 3) 150F hood
Gasoline Bulk Terminals & Storage	1) Vents, storage tanks	1) Afterburners, adsorbers, refrigeration	1) Direct exhaust	1) As required	1) 70-100F
Glass Manufacturing	1) Regenerative tank furnace 2) Weight hoppers and mixers	1) Baghouse, scrubber precipitator 2) Same as 1	1) Direct exhaust 2) Canopy	1) Fan capacity 2) 200 fpm/ft^2	1) 600-850F furnace 2) 100F mixers
Graphic Arts	1) Presses 2) Lithographics, metal decorating ovens	1) Adsorbers, afterburners 2) Afterburners	1) Hoods 2) Hoods	1) 3,000-11,000 cfm/press 2) 3,000-60,000 cfm/oven	1) 100F 2) 400-600F

Table 2.1 (Continued)

INDUSTRY	SOURCE	CONTROL SYSTEM	CAPTURE DEVICE	TYPICAL GAS FLOW DESIGN RATE	TYPICAL GAS TEMPERATURE
Gray Iron Foundries	1) Cupola 2) Electric arc furnace 3) Core oven 4) Shakeout	1) Afterburner-baghouse for closed cap, Afterburner-precipitator for closed cap, scrubber 2) Baghouse, scrubber precipitator 3) Afterburner 4) Baghouse	1) Direct exhaust 2) Direct exhaust, full/side draft hood 3) Direct exhaust 4) Full/side draft hood	1) Tuyere air + infil. door air + afterburner second air 2) 2000 cfm/ft^2 hood opening 3) Fan capacity 4) 200-500 cfm/ft^2 hood	1) 1200-2200F 2) ~2500F direct exh. ~400F hood 3) 150F 4) ~150F
Industrial & Utility Boilers	1) Boiler	1) Precipitator, baghouse	1) Direct exhaust	1) Fan capacity	1) 250-800F
Insulation Wire Varnish	1) Spray booths 2) Flow coating machines 3) Dip tanks 4) Roller coating machines	1) Adsorbers, absorbers, afterburners 2) Same as 1 3) Same as 1 4) Same as 1	1) Direct exhaust 2) Exhaust hood 3) Exhaust hood 4) Exhaust hood	1) 100-150 cfm/ft^2 booth opening	1) 100F
Iron Ore Benefication	1) Crusher 2) Sinter machine	1) Baghouse, scrubber 2) Same as 1	1) As required 2) As required	1) As required 2) As required	1) As required 2) As required
Iron & Steel (Sintering)	1) Sinter machine a) Sinter bed b) Ignition fce. c) Wind boxes 2) a) Sinter crusher b) Conveyors c) Feeders	1) Precipitator, baghouse, scrubber 2) Baghouse, scrubber	1) Down draft hood 2) Canopy hood	1) Based on bed size 2) 250 fpm hood face	1) 150-400F sinter machine 2) 70F conveyors
Kraft Recovery Furnaces	1) Recovery furnace and direct contact evaporator	1) Precipitator, scrubber	1) Direct exhaust	1) Primary and secondary air supply capacity	1) 350F
Lime Kilns	1) Vertical kilns 2) Rotary sludge kiln	1) Baghouse, scrubber, precipitator 2) Scrubber, precipitator	1) Direct exhaust 2) Direct exhaust	1) Combustion air rate 2) Combustion air rate	1) 200-1200F 2) 200-1200F
Maleic Anhydride	1) Benzene storage tanks, process vent & Vac. refin. vent	1) Adsorbers, afterburners	1) Direct exhaust	1) As required	1) 70-100F
Miscellaneous Refinery Sources	1) Vents, storage tank, etc.	1) Afterburner, flare adsorbers, absorbers refrigeration	1) As required	1) As required	1) As required

Table 2.1 (Continued)

INDUSTRY	SOURCE	CONTROL SYSTEM	CAPTURE DEVICE	TYPICAL GAS FLOW DESIGN RATE	TYPICAL GAS TEMPERATURE
Municipal Incinerator	1) Incinerator	1) Scrubber, precipitator, baghouse, afterburner	1) Direct exhaust	1) Combustion air fan capacity where applicable	1) 500-700F
Non-Metallic Minerals Industry	1) Miscellaneous sources	1) Scrubbers, baghouse	1) As required	1) As required	1) As required
Onshore Crude Oil Production	1) Vents, storage tanks	1) Adsorbers, afterburners, refrigeration	1) As required	1) As required	1) 70-100F
Organic Chemicals	1) Miscellaneous sources	1) Scrubbers, adsorbers, absorbers, refrigeration flares	1) As required	1) As required	1) As required
Paint Manufacturing	1) Varnish kettles	1) Afterburners	1) Exhaust hood	1) 100-300 cfm/200-375 gal. Kettle	1) 500F
Petroleum Catalytic Cracking	1) CO boiler from FCC	1) Precipitator	1) Direct exhaust	1) Regeneration air rate + boiler combustion air	1) 500F
Petroleum Storage	1) Vents, storage tanks	1) Afterburners, adsorbers, refrigeration	1) Direct exhaust	1) As required	1) 70-100F
Pharmaceuticals	1) Reactor 2) Crystallizer 3) Centrifuge 4) Filter, dryer 5) Dist. column	1) Adsorbers, refrigeration, incineration 2) Same as 1 3) Same as 1 4) Same as 1 5) Same as 1	1) Direct exhaust 2) Direct exhaust 3) Direct exhaust 4) Direct exhaust 5) Direct exhaust	1) 50-300 scfm 2) 50-300 scfm 3) 10-50 scfm 4) 10-800 scfm 5) 500-900 scfm	1) As required 2) As required 3) As required 4) As required 5) As required
Phosphate Fertilizer	1) Digester vent air 2) Filters 3) Sumps	1) Scrubber, baghouse 2) Same as 1 3) Same as 1	1) Hood 2) Same as 1 3) Same as 1	1) Process stream rate 2) Same as 1 3) Same as 1	1) 150F 2) Same as 1 3) Same as 1
Phosphate Rock Crushing	1) Crusher & screens 2) Conveyor 3) Elevators 4) Fluidized bed calciner, grinder & dryer	1) Baghouse, scrubber, precipitator 2) Same as 1 3) Same as 1 4) Same as 1	1) Canopy hood 2) Same as 1 3) Same as 1 4) Direct exhaust	1) 350 cfm/ft belt width at speeds ~200 fpm 500 cfm/ft belt width at speeds ~200 fpm 2) 100 cfm/ft of casing cross-section (elevator) 50 cfm/ft of screen area 3) Combustion air rate 4) Blower rate	1) 70F hoods 2) Same as 1 3) Same as 1 4) 600-1500F calciner

Table 2.1 (Continued)

INDUSTRY	SOURCE	CONTROL SYSTEM	CAPTURE DEVICE	TYPICAL GAS FLOW DESIGN RATE	TYPICAL GAS TEMPERATURE
Polyvinyl Chloride Production	1) Process equipment vents	1) Adsorbers, afterburners	1) Direct exhaust	1) Process gas stream rate	1) -15 to 130F
Portland Cement	1) Rotary kiln a) Wet b) Dry 2) Crushers and conveyors 3) Dryers	1) Precipitators, baghouses 2) Baghouses 3) Precipitators, baghouses	1) Direct exhaust 2) Canopy hoods 3) Direct exhaust	1) Combustion air rate where applicable 2) 250 fpm hood face 3) Same as 1	1) 150-850F kilns 2) 70F crushers and conveyors 3) 200F dryers
Primary Copper, Lead, Zinc Smelters	1) Roaster, converter	1) Precipitator, scrubber, absorber	1) Direct exhaust	1) As required	1) As required
Pulp and Paper	1) Fluidized bed reactor	1) Scrubber	1) Direct exhaust	1) Combustion air rate	1) 600-1500F
Refuse Waste Disposal	1) Furnace	1) Afterburner	1) Direct exhaust	1) As required	1) 500-700F
Rubber Products (Tires)	1) Rubber mill and mixers	1) Baghouse	1) Canopy hood	1) 100 fpm through face	1) 70F
Secondary Aluminum	1) Reverbatory furnace 2) El. induction furnace 3) Crucible furnace 4) Chlorinating station 5) Dross processing 6) Sweating furnace	1) Scrubber (low energy) + baghouse, precipitator 2) Same as 1 3) Same as 1 4) Same as 1 5) Same as 1 6) Same as 1	1) Canopy hood (hearths), direct exhaust 2) Same as 1 3) Same as 1 4) Same as 1 5) Same as 1 6) Same as 1	1) Max. plume vol. + 20% (hearths) 2) Infiltrated air 3) Same as 2 4) Same as 2 5) Same as 2 6) Same as 2	1) 1600F fluxing, 600F holding hearth 2) Based on type capture 3) Same as 2 4) Same as 2 5) Same as 2 6) Same as 2
Secondary Copper Smelters	1) Reverbatory furnace 2) Crucible furnace 3) Cupola & blast furnace 4) Converters 5. El. induction furnaces	1) Baghouse, scrubber, precipitator 2) Same as 1 3) Same as 1 4) Same as 1 5) Same as 1	1) Direct exhaust, canopy hood, full hood 2) Same as 1 3) Same as 1 4) Same as 1 5) Same as 1	1) 200 fpm/ft^2 canopy hood 2) Max. plume vol. + 20% 3) 1800 fpm infiltrated air (full hood) 4) Based on type capture 5) Same as 4	1) 2500F direct tap 2) Based on type capture 3) Same as 2 4) Same as 2 5) Same as 2
Service Stations	1) Loading rack	1) Adsorbers, refrigeration	1) Balanced system/ direct exhaust	1) Loading flow rate	1) 70-100F

Table 2.1 (Continued)

INDUSTRY	SOURCE	CONTROL SYSTEM	CAPTURE DEVICE	TYPICAL GAS FLOW DESIGN RATE	TYPICAL GAS TEMPERATURE
Sewage Sludge Incinerators	1) Multiple hearth incinerator 2) Fluidized bed incinerator	1) Scrubber 2) Same as 1	1) Direct exhaust 2) Same as 1	1) Combustion air blower capacity 2) Same as 1	1) 600 to 1500F 2) Same as 1
Surface Coatings - Spray Booths	1) Spray booth	1) Adsorber, afterburner	1) Canopy hood	1) 150 cfm/ft^2 hood, 100 fpm booth face velocity	1) 70F
Vegetable Oil Processing	1) Solvent extraction process	1) Adsorbers, scrubbers	1) As required	1) As required	1) 100F

1) The table and listings are only intended as a guide to illustrate the typical range of flow rates and temperatures that might be expected with the designated control systems. The source of these data are contained in Appendix C and cross-referenced to industries on page C-1. For further detail, the user can refer to the appropriate EPA control technique documents for the various industries and sources.

Table 2.2 DESIGN PARAMETERS FOR RESPECTIVE INDUSTRIES FOR HIGH EFFICIENCY PERFORMANCE[1,2]

Industry	Fabric Filter Air-to-Cloth Ratio			Venturi Scrubber	Precipitator
	Reverse Air	Pulse Jet	Mechanical Shaker	In. of Water	Drift Vel Ft/sec
Basic oxygen furnaces	1.5-2.0	6-8	2.5-3.0	40-60	.15-.25
Brick manufacturing	1.5-2.0	9-10	2.5-3.2	35	
Castable refractories	1.5-2.0	8-10	2.5-3.0		
Clay refractories	1.5-2.0	8-10	2.5-3.2	11	
Coal fired boilers				15	.22-.35
Detergent manufacturing	1.2-.15	5-6	2.0-2.5	10-40	
Electric arc furnaces	1.5-2.0	6-8	2.5-3.0		.12-.16
Feed mills		10-15	3.5-5.0		
Ferroalloy plants	2.0	9	2.0	40-80	
Glass manufacturing	1.5			65	.14
Gray iron foundries	1.5-2.0	7-8	2.5-3.0	25-60	.1-.12
Iron and steel (sintering)	1.5-2.0	7-8	2.5-3.0		.2-.35
Kraft recovery furnaces				15-30	.2-.3
Lime kilns	1.5-2.0	8-9	2.5-3.0	12-40	.17-.25
Municipal incinerators					.2-.33
Petroleum catalytic cracking				40	.12-.18
Phosphate fertilizer	1.8-2.0	8-9	3.0-3.5	15-30	
Phosphate rock crushing		5-10	3.0-3.5	10-20	.35
Polyvinyl chloride production		7			
Secondary aluminum smelters		6-8	2.0	30	
Secondary copper smelters		6-8			.12-.14

1) High Efficiency - an outlet loading of less than 0.04 gr/scf.

2) Source - see page C-1, Appendix C.

Table 2.3 EFFICIENCY OF CARBON ADSORPTION FOR SELECTED SOLVENTS AND SPECIFIED OPERATING CONDITIONS

Solvent	Average Inlet Concentration (ppm)	Acceptable Ceiling Concentration (ppm)	Lower Explosive Limit (% by volume in air)	Carbon[1] Adsorption Efficiency lb solvent/100 lb carbon
Acetone	1,000		2.15	8
Benzene	10	25	1.4	6
n-Butyl acetate	150		1.7	8
n-Butyl alcohol	100		1.7	8
Carbon tetrachloride	10	25	n	10
Cyclohexane	300		1.31	6
Ethyl acetate	400		2.2	8
Ethyl alcohol	1,000		3.3	8
Heptane	500		1	6
Hexane	500		1.3	6
Isobutyl alcohol	100		1.68	8
Isopropyl acetate	250		2.18	8
Isopropyl alcohol	400		2.5	8
Methyl acetate	200		4.1	7
Methyl alcohol	200		6.0	7
Methylene chloride	500	1,000	n	10
Methyl ethyl ketone	200		1.81	8
Methyl isobutyl ketone	100		1.4	7
Perchlorethylene	100	200	n	20
Toluene	200	300	1.27	7
Trichlorethylene	100	200	n	15
Trichloro trifluoroethane	1,000		n	8
V M & P Naphtha[2]	500		0.81	7
Xylene	100		1.0	10

NOTE:

1) Efficiencies are based on 200 cfm of 100 F solvent-laden air (at the specified concentrations) per hundred pounds of carbon per hour. Source: Manzone, R.R. et al., "Profitability Recycling Solvents from Process Systems", Hoyt Manufacturing corp, Pollution Engineering Oct. 1973. More precise carbon estimation procedures are given in Section 5.5

2) Varnish makers & painters naphtha.

Section 3

COST ESTIMATING PROCEDURES

Several methods of varying degrees of accuracy are available for estimating the capital costs of systems. These methods range from presenting overall installed costs on a per unit basis, to detailed cost estimates based on preliminary designs, schematics, and contractor quotes. The least accurate method is the equating of overall capital costs to a basic operating parameter such as tons per hour or cfm. An example is a typical installed cost for a fabric filtration system of approximately seven dollars per cfm. This figure is developed from average costs of many installations which may range from three to twelve dollars per cfm. The low end of the range might represent an installation using standard equipment, installed by plant personnel, and just marginally meeting current regulations. The high end of the cost range may represent a system designed for: 1) the inclusion of standby equipment and redundant systems, 2) overprovision for safety, 3) fully automated operation with complex controls, and 4) expensive materials of construction or other custom features. These factors affect both equipment and installation costs, and therefore the degree of accuracy produced using an estimating method based on cfm alone would, at best, provide accuracies in an "order of magnitude" category (probable accuracy of +50%, -30%) Ref. 149.

The detailed cost estimate, in turn, can produce accuracies of ±5 percent depending on the amount of perliminary engineering involved. These estimates take many months of engineering effort and require process and engineering flow sheets, material and energy balances, plot plans, and equipment arrangement drawings before a cost estimate can be developed. For first-cut estimating purposes, a technique for developing capital costs must be used that is between these two extremes that can provide accuracies of approximately ±20 percent.

The technique used in this manual for determining capital costs for a specifi pollution control system is based on the factored method of establishing direct and indirect installations costs as a function of known equipment costs. This approach is basically a modified "Lang Method" of cost estimating whereby cost factors for installation are applied to the cost of the equipment. The resulting cost estimates using this technique can provide accuracies of plus or minus 20 percent for new installations. This is somewhat better than a "study estimate" which has an error limit on the order of plus or minus 30 percent.

The cost factors developed in this manual are based on both quoted and estimated installation costs of pollution control systems. The annual operating costs for these systems are based on unit costs for utilities and operating and maintenance labor and materials together with fixed percentages of capital costs for the indirect costs.

3.1 Capital Costs

The capital costs of a pollution control system consisting of the delivered equipment costs for the control device and all the auxiliary equipment and appurtenances plus the direct and indirect costs of installation are shown in Table 3.1. The equipment costs represent a firm cost since these are obtainable from the supplier's quoted prices or from curves compiled from average costs for the specific type of equipment such as those provided in Section 4 and 5. The cost of installation can vary substantially from one system to another depending on such features as: 1) the degree of assembly of the control device; i.e., whether it is delivered as a packaged unit or must be field assembled, 2) the geographic location of the plant in regard to local wage rates and availability of contractors, 3) the topography of the land site (whether the land is within the battery limits or outside and must be purchased), 4) the availability of service facilities, i.e., whether electricity, water, steam, etc., are at or near the site, and 5) whether the equipment is to

TABLE 3.1 CAPITAL COSTING - (FABRIC FILTERS)

	1* TYPICAL COST FACTOR	X	2* COST ADJUSTMENT RANGE	=	3* SYSTEM COST FACTOR
DIRECT COSTS					
1) PURCHASED EQUIPMENT COSTS					
a) Control Device	Cost Per Section 5				
b) Auxiliary Equipment	Cost Per Section 4				
c) Instruments & Controls	0.10	X	.5 - 3	=	0.05 to 0.30
d) Taxes	0.03	X	.3 - 1.6	=	0.01 to 0.05
e) Freight	0.05	X	.2 - 2	=	0.01 to 0.10
TOTAL	1.00				1.00
2) INSTALLATION DIRECT COSTS					
a) Foundations & Supports	0.04				0.04
b) Erection & Handling	0.50	X	.2 - 2	=	0.10 to 1.0
c) Electrical	0.08				0.08
d) Piping	0.01				0.01
e) Insulation	0.07				0.07
f) Painting	0.02				0.02
g) Site Preparation	As Req'd.	X	0 - 2	=	0 to 2
h) Facilities & Buildings	As Req'd.	X	0 - 2	=	0 to 2
TOTAL	1.72				1.28 to 6.18
INDIRECT COSTS					
3) INSTALLATION INDIRECT COSTS					
a) Engineering & Supervision	0.10	X	.5 - 3	=	0.05 to 0.30
b) Construction & Field Expenses	0.20	X	.5 - 1.5	=	0.10 to 0.30
c) Construction Fee	0.10	X	.5 - 2	=	0.05 to 0.20
d) Start Up	0.01				0.01
e) Performance Test	0.01				0.01
f) Model Study	None				----
g) Contingencies	0.03	X	1 - 10	=	0.03 to 0.30
TOTAL	2.17				1.53 to 7.30

* Based on Tables 3.2 and 3.3.

be outside or enclosed in buildings. The cost of retrofitting an existing plant process may involve one or more of the conditions 1 to 5 plus it often involves the dismantling and removal of existing equipment, a task which could be both costly and time consuming.

In assessing the relationship between direct and indirect costs of installation to the cost of equipment, it is necessary to apply some adjustments to those cost items that have a minor impact on equipment costs but are heavily influenced by such items as plant size, plant location, safety and type of process. This is particularly true when considering the indirect costs such as engineering, construction fees, and contingencies. Cost factors for engineering and construction fees will depend on whether the system utilizes standard or custom designed equipment and if the process entails new technology or is simply a duplicate of an existing system. Contingencies may be based on whether the process is firm or tentative and subject to changes.

The cost factors and cost adjustments must also be evaluated on a per system basis. For instance, the cost of piping may be negligible for a fabric filtration system but it becomes an accountable item for scrubbers or wet precipitators. The cost of insulation is only relevant to those processes that handle hot gas streams or provide some type of cooling in the collection process.

The use of the cost factors and adjustments must be applied with some engineering judgement. The application of these factors will depend, to some extent, on what is included in the cost of the equipment. As shown in Table 3.1, a typical cost factor can be developed which represents the average cost factor based on the analysis of several similar systems. In the analysis of these systems, a deviation in some cost factors for the same item can be attributed to some cost adjustment. For instance, if a fabric filter is purchased as a standard unit and factory-assembled, the equipment cost will be higher than the same unit shipped "broken-down" or in modules; however, the installation costs for handling and erection will be lower for the factory-assembled unit. If a typical cost factor for handling and erection was applied to the equipment cost of both units without a cost adjustment, the error in the handling and erection costs of the factory-assembled unit essentially would be compounded. Therefore, the typical cost factors, shown in column 1 of Table 3.1, which indicate the average values for each component cost for a particular type of pollution control system, are then multiplied by a cost adjustment to establish the system cost factor for a specific application. The cost adjustments are used for any type of system and are solely provided as modifiers for the cost factor. The cost adjustment can be considered as a means of compensating for cost variations that are not directly attributable to the cost of equipment. The system cost factor is then multiplied by the total equipment cost to determine the estimated component cost in dollars. A description of the capital cost components with their cost factors, adjustments, and their usage is presented in the following sections.

3.1.1 Purchased Equipment Costs

The purchased equipment costs represent the delivered costs of the control device, auxiliary equipment, and instrumentation. These costs are developed by first establishing the design and operating characteristics of the equipment that will satisfy the pollution control requirements of a specific industrial process. The F.O.B. costs are then established from curves, graphs, and data found in Sections 4 and 5 of this manual which cover the cost of the control device and selected auxiliary equipment. The prices listed represent flange-to-flange costs and generally include internal electricals and controls except where noted. Instrumentation is not included in Sections 4 and 5 since it is usually provided as an optional feature in most equipment costs. The typical cost factor for instrumentation can be considered as 10% of the equipment costs as shown in Table 3.1 (Ref. 156). A cost adjustment is also provided for this component cost as shown in Table 3.2. Freight costs within the U.S. are generally 5% of the equipment cost although a cost adjustment must also be included for unusually remote or distant sites as shown in Table 3.2 (Ref. 150). The purchased equipment costs, which includes the F.O.B. equipment cost, instrumentation, freight and taxes, then becomes the basis for determining the direct and indirect installation costs. This is done by multiplying the appropriate factor for each element by the purchased equipment cost (NOTE: Table 3.1 expresses the purchased equipment cost as unity).

Since the cost of delivered purchased equipment represents the basis for determining installation costs, those items that are not field fabricated should be accounted for as purchased components and included in the purchased equipment costs. In typical factorial cost estimating methods such as the Lang method, the cost of items such as hoods, ducting, etc., are only included in the installation costs and usually represented as a percentage of equipment costs. These costs, however, can be as much as the cost of the control device itself. Since most of the ductwork is shop fabricated, cost of the ductwork should be developed for each specific application and included in the cost of auxiliary equipment. Curves are provided in Section 4 to estimate the cost of these components. Only the handling, erection, insulation, and painting of the ductwork are included in the installation costs and are designated as a percentage of the total equipment costs. Thus, the cost of items normally shop fabricated are accurately accounted for as

TABLE 3.2 COST ADJUSTMENTS*

	COST ADJUSTMENT
A) INSTRUMENTATION	
1) Simple, continuous manually operated	0.5 to 1.0
2) Intermitten operation, modulating flow with emissions monitoring instrumentation	1.0 to 1.5
3) Hazardous operation with explosive gases and safety backups	3
B) FREIGHT	
1) Major metropolitan areas in continental U.S.	0.2 to 1.0
2) Remote areas in continental U.S.	1.5
3) Alaska, Hawaii, and foreign	2
C) HANDLING AND ERECTION	
1) Assembly included in delivered cost with supports, base, skids included. Small to moderate size equipment	0.2 to 0.5
2) Equipment supplied in modules, compact area site with ducts and piping less than 200 ft. in length. Moderate size system	1
3) Large system, scattered equipment with long runs. Equipment requires fabrication at site with extensive welding and erection	1 to 1.5
4) Retrofit of existing system; includes removal of existing equipment and renovation of site. Moderate to large system	2
D) SITE PREPARATION	
1) Within battery limits of existing plant; includes minimum effort to clear, grub, and level	0
2) Outside battery limits; extensive leveling and removal of existing structures; includes land survey and study	1
3) Requires extensive excavation and land ballast and leveling. May require dewatering and pilings	2

* Based on data obtained in refs. 150, 156, 159.

TABLE 3.2 COST ADJUSTMENTS (CONTINUED

	COST ADJUSTMENT
E) FACILITIES & BUILDINGS	
1) Outdoor units, utilities at site	0
2) Outdoor units with some weather enclosures. Requires utilities brought to site, access roads, fencing, and minimum lighting	1
3) Requires building with heating and cooling, sanitation facilities, with shops and office. May include railroad sidings, truck depot, with parking area	2
F) ENGINEERING & SUPERVISION	
1) Small capacity standard equipment, duplication of typical system, turnkey quote	0.5
2) Custom equipment, automated controls	1 to 2
3) New process or prototype equipment, large system	3
G) CONSTRUCTION & FIELD EXPENSES	
1) Small capacity systems	.5
2) Medium Capacity systems	1
3) Large capacity systems	1.5
H) CONSTRUCTION FEE	
1) Turnkey project, erection and installation included in equipment cost	.5
2) Single contractor for total installation	1
3) Multiple contractors with A&E firm's supervision	2
I) CONTINGENCY	
1) Firm process	1
2) Prototype or experimental process subject to change	3 to 5
3) Guarantee of efficiencies and operating specifications requiring initial pilot tests, deferment of payment until final certification of EPA tests, penalty for failure to meet completion date or efficiency.	5 to 10

purchased equipment. The cost burden for handling and erecting these items becomes a smaller portion of the total installed cost of the system, and hence, any inaccuracies in the percentage factors will have a lesser effect on the total estimated cost of the system.

3.1.2 Installation Costs

Installation costs consist of the direct expenses of material and labor for foundations, structural supports, handling and erection, electrical, insulation, painting, site preparation, and facilities; plus the indirect expenses for engineering and supervision, construction and field expenses, construction fees, start up, performance tests, model studies, and contingencies. In considering the direct costs, site preparation, buildings and facilities are items that have little or no relationship to the cost of the purchased equipment and therefore some cost adjustment, as shown in Table 3.2, must be used to compensate for added costs due to unusual requirements. Examples of unusual site preparation would be the removal of existing structures before construction or a potential site which is a bog or swamp. Although handling and erection are related to equipment costs, some adjustment must also be made for either field erection or factory assembly of the control device and auxiliary equipment as well as the type of installation, i.e., new or retrofit of an existing process.

Variations in the indirect expenses can be substantial since items such as engineering, construction fees, and contingencies are related to contracting methods and the overall magnitude of the project rather than the equipment costs. These items all require some adjustment based on system size and contracting arrangement. Other cost items such as model studies may appear in unusual circumstances such as large electrostatic precipitator systems or other systems where the level of previous experience may be limited.

In evaluating the installation costs of all systems, it is assumed that the installation is performed by an outside contractor and not by plant personnel. In addition, the cost factors will change for different types of systems since many of the components are dissimilar items. Table 3.3 summarizes the estimated cost factors for each system. Cost adjustments of Table 3.2 should be applied to these cost factors, where appropriate, to develop the estimated capital costs of a specific application.

3.2 Annualized Costs

The typical annualized costs, shown in Table 3.4, consist of the direct expenses of labor and materials for operation and maintenance, the cost of replacement parts, utility costs, and waste disposal; plus the indirect costs of overhead, taxes, insurance, general administration and the capital recovery charges. The unit costs are only samples and can vary significantly from installation to installation. The direct costs of labor and utilities are based on average rates as of December, 1977 that have been developed by the Bureau of Labor Statistics. The cost of replacement parts is based on the purchased list price of those components and materials that have a known limited life or replacement schedule. Waste disposal costs are only applicable to some systems where the collected pollutant has no value and must be removed to a disposal site. In most cases, the controlled pollutant can either be recovered and used again in the primary process or is disposed of by the pollution control system itself, e.g., by combustion in incinerators and flares.

The indirect operating costs are basically related to the capital investment with the possible exception of overhead. Overhead expenses include the cost of employee fringe benefits, medical and property protection, cafeteria expenses, etc. and are accounted for as a percentage of direct salaries or payroll.

TABLE 3.3 CAPITAL COST SUMMARY*

DIRECT COSTS	ESP	VS	FF	T&CI	ADS	ABS	R	F
1) PURCHASED EQUIPMENT COSTS								
a) Control Device	As Req'd	--------	--------	--------	--------	--------	--------	--------
b) Auxiliary Equipment	As Req'd	--------	--------	--------	--------	--------	--------	--------
c) instruments & Controls	0.10	--------	--------	--------	--------	--------	--------	--------
d) Taxes	0.03	--------	--------	--------	--------	--------	--------	--------
e) Freight	0.05	--------	--------	--------	--------	--------	--------	--------
TOTAL	1.00	--------	--------	--------	--------	--------	--------	--------
2) INSTALLATION DIRECT COSTS								
a) Foundations & Supports	0.04	0.06	0.04	0.08	0.08	0.12	0.08	0.12
b) Erection & Handling	0.50	0.40	0.50	0.14	0.14	0.40	0.14	0.40
c) Electrical	0.08	0.01	0.08	0.04	0.04	0.01	0.08	0.01
d) Piping	0.01	0.05	0.01	0.02	0.02	0.30	0.02	0.02
e) Insulation	0.02	0.03	0.07	0.01	0.01	0.01	0.10	0.01
f) Painting	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.01
g) Site Preparation**	As Req'd	--------	--------	--------	--------	--------	--------	--------
h) Facilities & Buildings**	As Req'd	--------	--------	--------	--------	--------	--------	--------
TOTAL	1.67	1.56	1.72	1.30	1.30	1.85	1.43	1.57
INDIRECT COSTS								
3) INSTALLATION INDIRECT COSTS								
a) Engineering & Supervision	0.20	0.10	0.10	0.10	0.10	0.10	0.10	0.10
b) Construction & Field Expenses	0.20	0.10	0.20	0.05	0.05	0.10	0.05	0.10
c) Construction Fee	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
d) Start Up	0.01	0.01	0.01	0.02	0.02	0.01	0.02	0.01
e) Performance Test	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
f) Model Study	0.02	----	----	----	----	----	----	----
g) Contingencies	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
TOTAL	2.24	1.91	2.17	1.61	1.61	2.20	1.74	1.92

* Values based on average of cost factors reduced from cost estimates.(Ref. 148, 160)

** Costs for site preparation, facilities, and buildings can be obtained from Reference 171.

TABLE 3.4 BASIS FOR ESTIMATING ANNUALIZED COSTS

DIRECT OPERATING COSTS	COST FACTOR	REFERENCE
1) Operating Labor		USDL, BLS average mill workers rate $6.56/h
a) Operator	$7.87/man-hour	plus fringes of 20%. May 1977.
b) Supervisor	15% of 1a	Ref. 150
2) Operating Materials	As Required	
3) Maintenance		
a) Labor	$8.66/man-hour	Hourly rate of 10% premium over operating labor
b) Material	100% of 3a	
4) Replacement Parts	As Required	
5) Utilities		USDL, BLS Consumer Price Index for
a) Electricity	$0.0432/Kwh	500/Kw/mo., May, 1977.
b) Fuel Oil	$0.47/gal	USDL, BLS Consumer Price Index, May 1977
c) Natural Gas	$1.98/Mcf	USDL, BLS Consumer Price Index, May 1977
d) Plant Water	$0.25/1000 gal	Ref. 156 updated 1977
e) Water Treatment & Cooling Water	$0.10/1000 gal	Ref. 156 updated 1977
f) Steam	$5.04/Mlb	Fuel @ $4.19/M Lb steam plus - 16% oper & Main.
g) Compressed Air	$0.02/1000 cf	Ref. 156 updated 1977
6) Waste Disposal	$5-10/Ton	
INDIRECT OPERATING COSTS		
7) Overhead	80% of 1a + 1b + 3a	Ref. 150
8) Property Tax	1% of capital costs	Ref. 150
9) Insurance	1% of capital costs	Ref. 150
10) Adminstration	2% of capital costs	Ref. 150
11) Capital Recovery Cost	0.16275 (as an example of 10% and an equipment life of 10 years)	
CREDITS		
12) Recovered Product	As Required	

The operating costs must be adjusted for any credits that are obtained from the reuse or sale of recovered products or from the recovery of heat and energy from the process. Credits such as solvent recovery can significantly offset control expenses and must be considered as an important factor in an accurate cost analysis.

3.2.1 Direct Operating Costs

Labor and material costs for operation and maintenance of pollution control systems vary substantially between plants due to the degree of automation of the system, equipment age, characteristics of the gas stream, operating periods and some generalizations must be made to develop a reasonable method of estimating these costs. Normally these costs represent from 2 to 8 percent of the total annualized costs with the remainder reflecting the cost of utilities and capital charges. In general, operating labor and supervision will be reduced with increased system automation. Small systems which operate intermittently or on demand may require a full time operator for start-up, control, and shutdown while the system is in operation. In contrast, larger automated systems operating continuously may only require a short period per shift for monitoring purposes. The total annual labor cost is also a function of the number of 8-hour operating shifts per year. Small plants may be expected to operate one shift per day, five days per week, and fifty weeks per year while large plants such as those in the basic metals, petroleum, and chemical industries would be expected to operate three shifts per day for 365 days. The operator labor, therefore, should be estimated on a man-hours per shift basis for the particular types of system. For large, automated, continuously operated systems, the operating labor can be estimated as shown in Table 3.5. Estimates of maintenance labor are also provided for large capacity systems handling non-corrosive materials. These estimates only reflect the cost of preventative maintenance. Where periodic

TABLE 3.5 ESTIMATED LABOR HOURS PER SHIFT*

CONTROL DEVICE	OPERATING LABOR (man-hours/shift)	MAINTENANCE LABOR (man-hours/shift)
Fabric Filters	2 - 4	1 - 2
Precipitators	.5 - 2	.5 - 1
Scrubbers	2 - 8	1 - 2
Incinerators	.5	.5
Adsorbers	.5	.5
Absorbers	.5	.5
Refrigeration	.5	.5
Flares	-	.5

* Based on discussions with manufacturers and operators with corroborating data from refs. 78, 82, 126 and 141.

replacement of major parts are required such as the replacement of filter bags in a fabric filter or the replacement of adsorbent in adsorbers, the labor cost for replacement should be equal to the material cost of the replacement parts. For small to medium size systems where the installed cost is approximately $100,000, or less, the total cost of maintenance is assumed to be 5 percent of the installed capital cost.

The annual cost of replacement parts represents the cost of the parts or components divided by their expected life. Replacement parts are those components and materials such as filter bags, catalyst, and absorbents which have a limited life and are expected to be replaced on a periodic schedule. An estimate of the life of the parts as well as equipment, as shown in Table 3.6, is based on a qualitative judgement of the type of application, maintenance service and duty cycle. The guideline for average life represents a process operating continuously with 3 shifts per day , 5 to 7 days per week, handling moderate concentrations of non-abrasive dusts or non-corrosive gases. The guideline for low life applications is based on a continuous process handing moderate to high temperature gas streams with high concentrations of corrosive gases or abrassive dusts. Applications having high life expectancies for parts and equipment would be those operating intermittantly or approximately one shift per day with gas streams with low concentrations and at ambient gas stream temperatures.

The cost of waste disposal considers only the removal and hauling of a dry contaminant to a nearby landfill area by an outside contractor.

To assist the user in developing the approximate utility costs for the auxiliary equipment and control devices, the following equations and data are provided.

TABLE 3.6 GUIDELINES FOR PARTS AND EQUIPMENT LIFE*

MATERIALS AND PARTS LIFE	LOW (Years)	AVERAGE (Years)	HIGH (Years)
Filter bags	.3	1.5	5
Adsorbents	2	5	8
Catalyst	2	5	8
Refractories	1	5	10
EQUIPMENT LIFE			
Electrostatic Precipitators	5	20	40
Venturi Scrubbers	5	10	20
Fabric Filters	5	20	40
Thermal Incinerators	5	10	20
Catalytic Incinerators	5	10	20
Adsorbers	5	10	20
Absorbers	5	10	20
Refrigeration	5	10	20
Flares	5	15	20

* Based on discussions with manufacturers and operators with corroborating data from refs. 19, 20, 37, 38, 40, 78 and 82.

Fan Power

The horsepower for various fans is shown in Section 4, however, the following formulas can also be used.

$$kwh = 0.746\ (hp)(H) = \frac{0.746\ (CFM)(\Delta P)(SG)(H)}{6356\ n}$$

where:

kwh = kilowatt-hours

hp = horsepower

CFM = actual volumetric flow rate, acfm

ΔP = pressure loss, inches WG

n = efficiency, usually 60 - 70%

H = hours of operation

SG = specific gravity as compared to air @ 70°F, 29.92 inches mercury.

Pump Power

The horsepower for pumps operating at various flow rates and pressure levels is shown in Section 4, however, the following formulas can also be used.

$$kwh = 0.746\ (hp)(H) = \frac{0.746\ (GPM)(hd)(SG)(H)}{3960\ n}$$

where:

GPM = flow rate, U.S. gpm

hd = head of fluid, feet

SG = specific gravity relative to water @60°F, 29.92 inches mercury

Baghouse Power (auxiliaries, motors, etc.)

Horsepower requirements for baghouse shaker motors, reverse air fan motors, etc. can be estimated at approximately 0.5 hp per 1000 sq. ft. of cloth. Power usage will depend on dust loading and cleaning cycle. Assuming a 50% usage factor, power requirements would be approximately 0.2 Kwh per 1000 sq. ft.

Precipitator Power

For approximation purposes, the power requirements for a precipitator can be assumed to be 1.5 watts per square foot of collection area, the range varying from 0.3 to 3 watts per square foot (ref. 168).

Incinerator Fuel

The fuel requirements for incinerators depends on the exhaust gas flow rate, the inlet, outlet, and combustion temperatures, inlet gas composition, and control efficiency. The utility costs for incinerators can be determined from the operating cost curves and fuel requirements developed in the EPA manual 450/3-76-031 "Report of Fuel Requirements, Capital Cost and Operating Expense for Catalytic and Thermal Afterburners", ref. 141.

3.2.2 Indirect Operating Costs

The indirect operating costs include the cost of taxes, insurance, administration expenses, overhead, and capital charges. Taxes, insurance, and administration can collectively be estimated at 4 percent of the capital costs while overhead charges can be considered as 80 percent of the labor charges for operation and maintenance of the system. The annualized capital charges reflect the costs associated with capital recovery over the depreciable life of the system and is determined as follows:

$$\text{Capital Recovery Cost} = (\text{capital costs}) \times \frac{i\,(1 + i)^n}{(1 + i)^n - 1}$$

where:

i = annual interest rate

n = capital recovery period

For average interest rates of 10 percent over a recovery period of 10 years, the capital recovery cost factor amounts to 0.16275 and the annual capital charges are accounted for as 0.16275 times the capital costs.

For a 20-year period, the capital recovery cost decreases to 0.11746 times the capital costs. There are other depreciation methods such as Straight-line, Declining Balance, etc. which can be used. The Capital Recovery Factor method is preferred by the EPA and is used in this manual.

Section 4

AUXILIARY EQUIPMENT

The gas cleaning methods used by industry today are categorized by the technique of gas or particulate removal. These techniques include: (1) electrostatic precipitation, (2) fabric filtration, (3) wet scrubbing, (4) incineration, (5) adsorption, (6) absorption, (7) refrigeration, and (8) flares. The properties and characteristics of the particular gas stream will generally dictate which control option is appropriate. In some cases, several techniques may be suitable or the selection of one type in lieu of the others may be based on efficiency and/or total costs (capital, maintenance, and operating).

For each technique selected in a particular application, a certain amount of auxiliary equipment must be utilized with the control device for the efficient operation of the gas cleaning system. The types of auxiliary equipment required will depend on the application. Hot processes may require pre-coolers before the control device or the addition of moisture may be required for proper operation of the control device. The selection of the auxiliary equipment is directly related to the size and operating characteristics of the control device. Therefore, to develop the gas stream inlet parameters to the control device, it is necessary to select and size the auxiliary equipment which may affect those parameters. Since most control systems require the same auxiliary equipment, a description and estimated cost of the auxiliary equipment is presented first and followed by the description of the control devices and system costs.

The arrangement of the auxiliary equipment with respect to the control device is shown in Figure 4-1. In general, all systems will require some auxiliary equipment such as fans and ductwork. The use of other auxiliary equipment will be dictated by the physical characteristics of the pollutant and gas stream, and the operating characteristics of the control device. Descriptions of the various components that may be included as auxiliary equipment for a system are provided in the following subsections.

4.1 Capture Hoods

Although a variety of hood configurations are used throughout industry, they can usually be catagorized as either canopy hoods or semi-closed hoods. Canopy hoods are defined as round or rectangular hoods mounted at a distance from the pollutant source so that the majority of the collected gas consists more of induced air than the volume of generated fume, dust or gas. Semi-closed hoods are described as enclosures attached to or comparatively near the source of pollutants so that the collected gas is primarily the generated pollutant and the remaining air is induced through openings in the enclosure for operational purposes.

The type and location of the capture device is directly related to the volumetric flow for the system. For example, for fume capture at the source, a relatively small volumetric exhaust rate is required to contain and capture the dust or pollutant. As the capture device is moved farther from the source, the fume is allowed to disperse and entrain outside air. The resulting dust envelope or plume increases in size as it mixes with the air, necessitating a larger capture device to contain it. As the distance between the source and the capture device increases, the volumetric flow rate for the control system also increases. Since the cost of a control system is closely related to

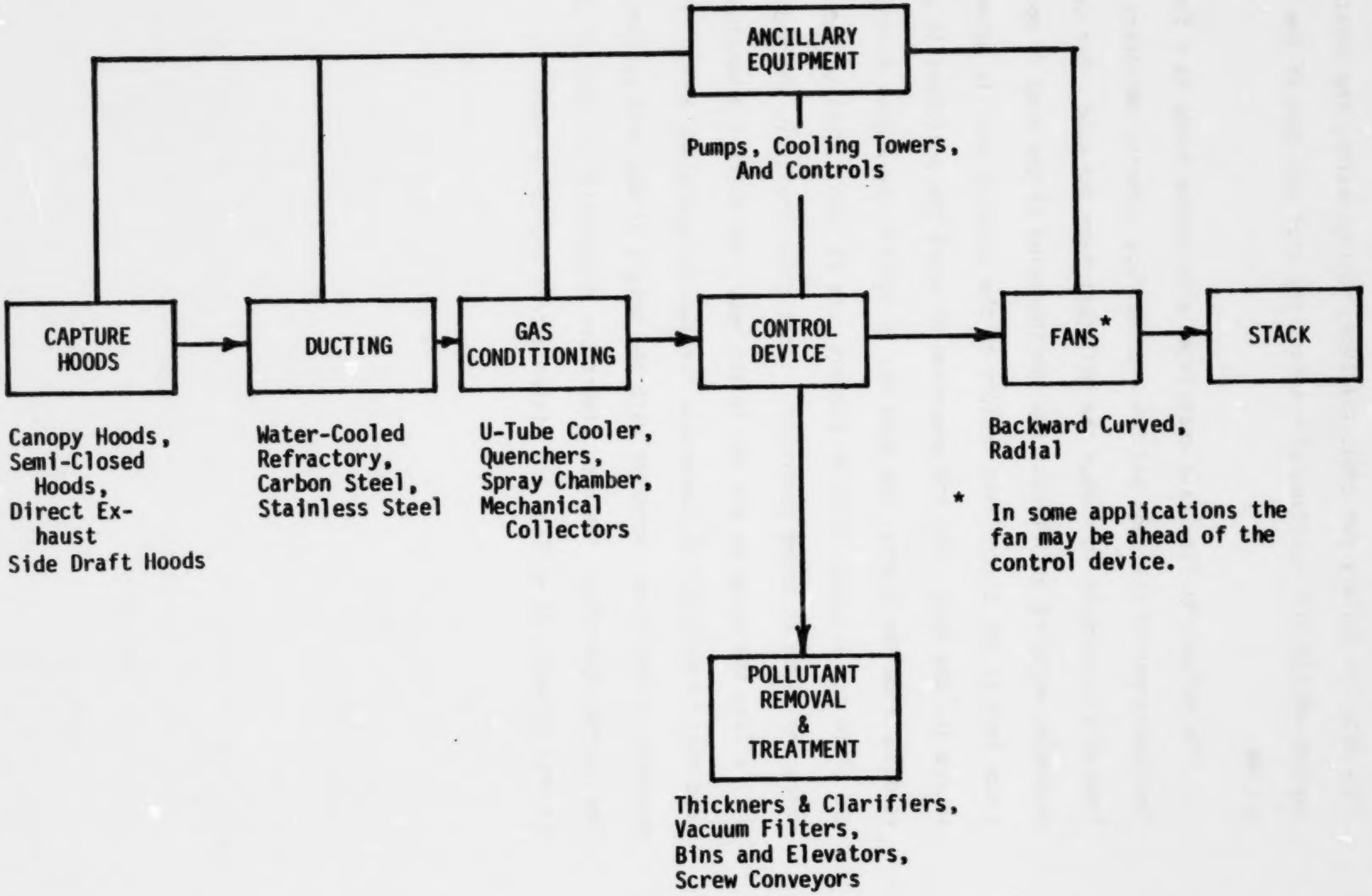

ANCILLARY EQUIPMENT
Pumps, Cooling Towers, And Controls
CAPTURE HOODS
DUCTING
GAS CONDITIONING
CONTROL DEVICE
FANS*
STACK
Canopy Hoods, Semi-Closed Hoods, Direct Exhaust Side Draft Hoods
Water-Cooled Refractory, Carbon Steel, Stainless Steel
U-Tube Cooler, Quenchers, Spray Chamber, Mechanical Collectors
Backward Curved, Radial
* In some applications the fan may be ahead of the control device.
POLLUTANT REMOVAL & TREATMENT
Thickners & Clarifiers, Vacuum Filters, Bins and Elevators, Screw Conveyors

Figure 4-1 CONTROL SYSTEM FLOW CIRCUIT

flow rate (in dollars per cfm), the type, configuration, and location of the capture device will substantially affect the size and cost of the overall system.

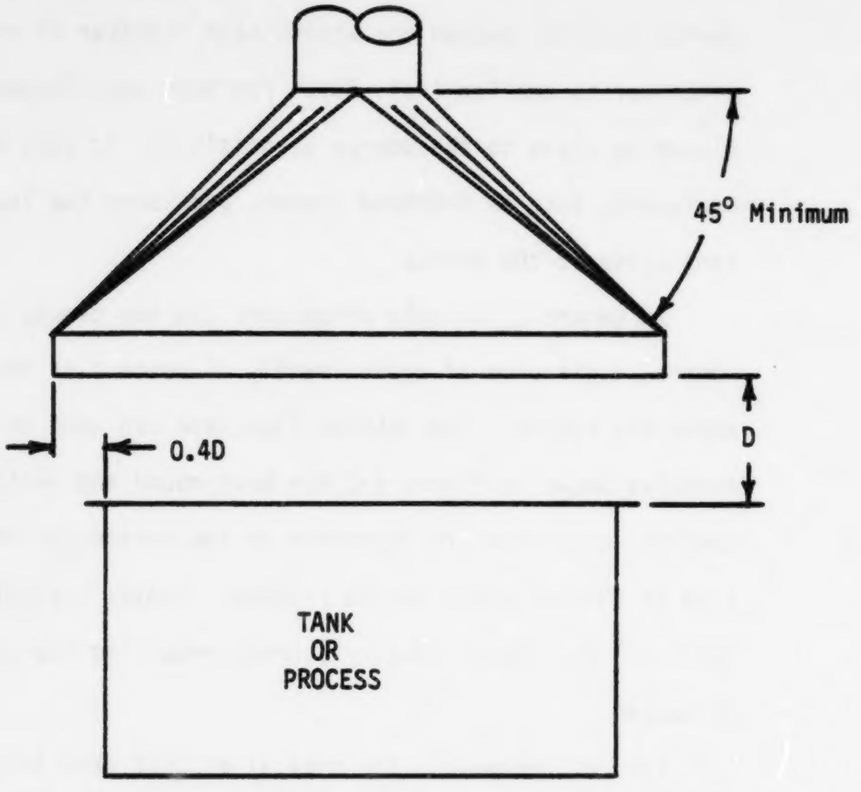
The volumetric flow rate associated with canopy hoods is a function of the dimensions of the hood and the average face velocity necessary to cause induced air currents to direct the pollutant into the hood. For cold processes emitting pollutants, the configuration of the hood is most important since this is the controlling feature of the velocity profile between the source and the hood. For hot processes or where the pollutant is given a velocity from the source, the hood has to contain the actual dimensions of the plume and evacuate it at an exhaust rate at least equal to the rate at which the plume is being generated. Since cross drafts in the operating area will affect the plume on the way to the hood, the overall dimensions of the hood must be enlarged to compensate for the maximum plume drift. The lateral movement of the plume increases with the height of the hood opening above the source; therefore, the hood dimensions substantially increase due to this lateral movement as well as the distance from source to hood.

Canopy hoods can be round or rectangular, and high or low. A hood may be considered a low canopy hood when the distance between the hood and the source does not exceed the approximate diameter of the source, or 3 feet, whichever is smaller (ref. 88). For best ventilation, the canopy should be placed as close to the source as possible. In some cases the operation of equipment, such as overhead cranes, precludes the location of the hood being very close to the source.

In general, for cold processes, the low canopy should extend around the source, a distance of approximately 40 percent of the height of the canopy above the source. The exhaust flow rate can then be determined by the general formulas shown in Figure 4-2 for both round and rectangular hoods. The required control velocities are dependent on the particular characteristics and evolution of the pollutant in the process. Typical velocities are outlined in Table 4.1 for those industry sources requiring low canopy hoods on cold processes.

For hot processes, the typical minimum ventilation rates normally required for low rectangular or circular canopy hoods can also be determined from the formulas in Table 4.1. The differential temperature (ΔT) represents the temperature difference between the source and the ambient air. This is a generalized method of sizing low canopies and exceptions and modifications to this method are described in Reference 88.

The sizing of high canopy hoods over hot processes becomes considerably more complicated. The buoyant effect of the plume is caused by the density differences between the source and the surrounding air. As the hot gases move upward, they entrain additional air and the plume expands and cools. The volume of the plume as a function of height above a circular source can be expressed as:



Not to be used where material is toxic and worker must bend over tank or process.

Side curtains are necessary when extreme cross-drafts are present.

Q = 1.4PDV	for open type canopy. P = perimeter of tank, feet. V = 50-500 fpm.
Q = (W+L)DV	for two sides enclosed. W & L are open sides of hood. V = 50-500 fpm.
Q = WDV or LDV	for three sides enclosed. (Booth) V = 50-500 fpm.

Figure 4-2 LOW CANOPY HOODS FOR COLD PROCESSES (ref. 151)

Table 4.1 MINIMUM VELOCITIES AND VENTILATION RATES FOR LOW CANOPY HOODS

RANGE OF CAPTURE VELOCITIES FOR COLD PROCESSES (ref. 151)

Condition of Dispersion of Contaminant	Examples	Capture Velocity, fpm
Released with practically no velocity into quiet air.	Evaporation from tanks; degreasing, etc.	50-100
Released at low velocity into moderately still air.	Spray booth; intermittent container filling; low speed conveyor transfers; welding; plating; pickling	100-200
Active generation into zone of rapid air motion.	Spray painting in shallow booths; barrel filling; conveyor loading; crushers	200-500
Released at high initial velocity into zone of very rapid air motion.	Grinding; abrasive blasting, tumbling	500-2000

MINIMUM VENTILATION RATES FOR HOT PROCESSES (ref. 88)

Low Circular Hoods:

$$Q = 4.7\ (D)^{2.33}(\Delta T)^{.42}$$

where Q = ventilation rate, cfm
D = diameter of hood, ft.
ΔT = temperature difference between hot source and ambient temperature, ^{o}F

Low Rectangular Hoods:

$$Q = 6.2\ (W)^{1.33}(L)\ (\Delta T)^{.42}$$

where Q = ventilation rate, cfm
W = width of canopy, ft.
L = length of canopy, ft.
ΔT = temperature difference between hot source and ambient temperature, ^{o}F

$$Q = 7.4(h + 2d)^{1.5} (H)^{.33}$$

where Q = plume volume, cfm

h = height above source, ft

d = diameter of source, ft

H = heat transfer rate from source to plume, Btu/min.

The plume volume from a rectangular source can be determined as follows:

$$Q = 18.5(h + 2w)^{.59}[L - w + 0.5(h + 2w)^{.88}] (H)^{.33}$$

where L = length of source, ft.

w = width of source, ft.

The predominant factor in this expression is the rate of heat transfer to the plume. A complete discussion of the methods of determining this heat transfer rate is given in References 88 and 152. Since the canopy hood at a given height above the source is required to collect and exhaust this plume, the volumetric flow rate must equal or exceed the plume volume.

The semi-closed hood can be designed in many different configurations which generally enclose the pollutant source. The exhaust rate with these devices is much lower than that from a canopy hood since collection is accomplished at the source. In order to contain the pollutant, the semi-closed hood is usually maintained at a slight negative pressure to insure inward flow of aspirated air. The velocity of the air through the openings is a function of the internal static pressure. Different velocities are required for different applications. In addition, the sizing of the hood and the required exhaust volume will depend on the particular process being controlled and the size of the source. Semi-closed hoods operating on hot processes may need to be fabricated from special materials or water-cooled.

Because of the variations in applications and designs for each source, the design and estimated costs for semi-enclosed hoods should be determined from the data and curves illustrated in Reference 88. For the purposes of this manual, only canopy hoods will be considered.

Figures 4-3 through 4-6 contain data for estimating the equipment costs for canopy hoods. Hood dimensions can be determined from Figure 4-2 or from recommendations in references 88, 129, 151 and 152 for most applications.

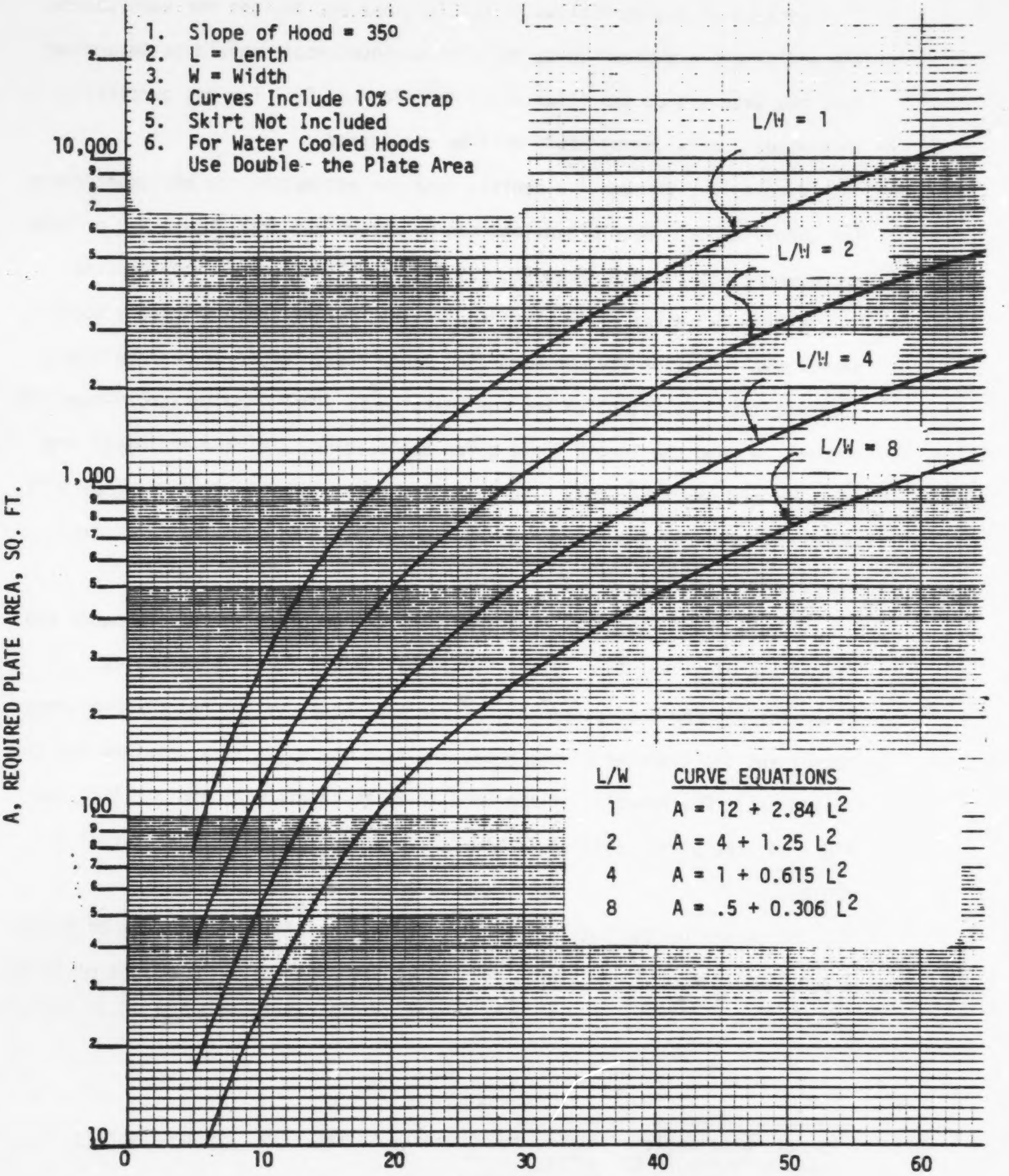
Figure 4-3 gives plate area requirements for rectangular canopy hoods and Figure 4-5 gives the corresponding labor costs for 10 Ga. carbon steel construction. To establish the equipment cost, determine the length-to-width ratio (L/W) and the length for a given application, and read the plate area required and the labor cost. For example, if the hood is 20 ft long by 5 ft wide, the L/W = 4, the plate required is approximately 250 ft^2, and the fabrication labor cost is approximately $425.

Figure 4-4 gives plate area requirements for circular capture hoods and Figure 4-6 gives the labor costs for 10 Ga. carbon steel construction. Determine the angle of slope[*], θ, of the hood cone (or the height-to-diameter ratio) and the diameter of the hood, and read the plate area required and the labor cost. For example, if the hood is 20 ft in diameter and $\theta = 50°$, the H/D = .6, the plate required is 550 ft^2, and the fabrication labor cost is $2010.

To determine the total fabricated price, the plate weight must be calculated, including 20% additional for structural supports. The weight of 10 Ga. carbon steel is 5.625 lb/ft^2. The weight of 1/4" plate is about 10.30 lb/ft^2.

---

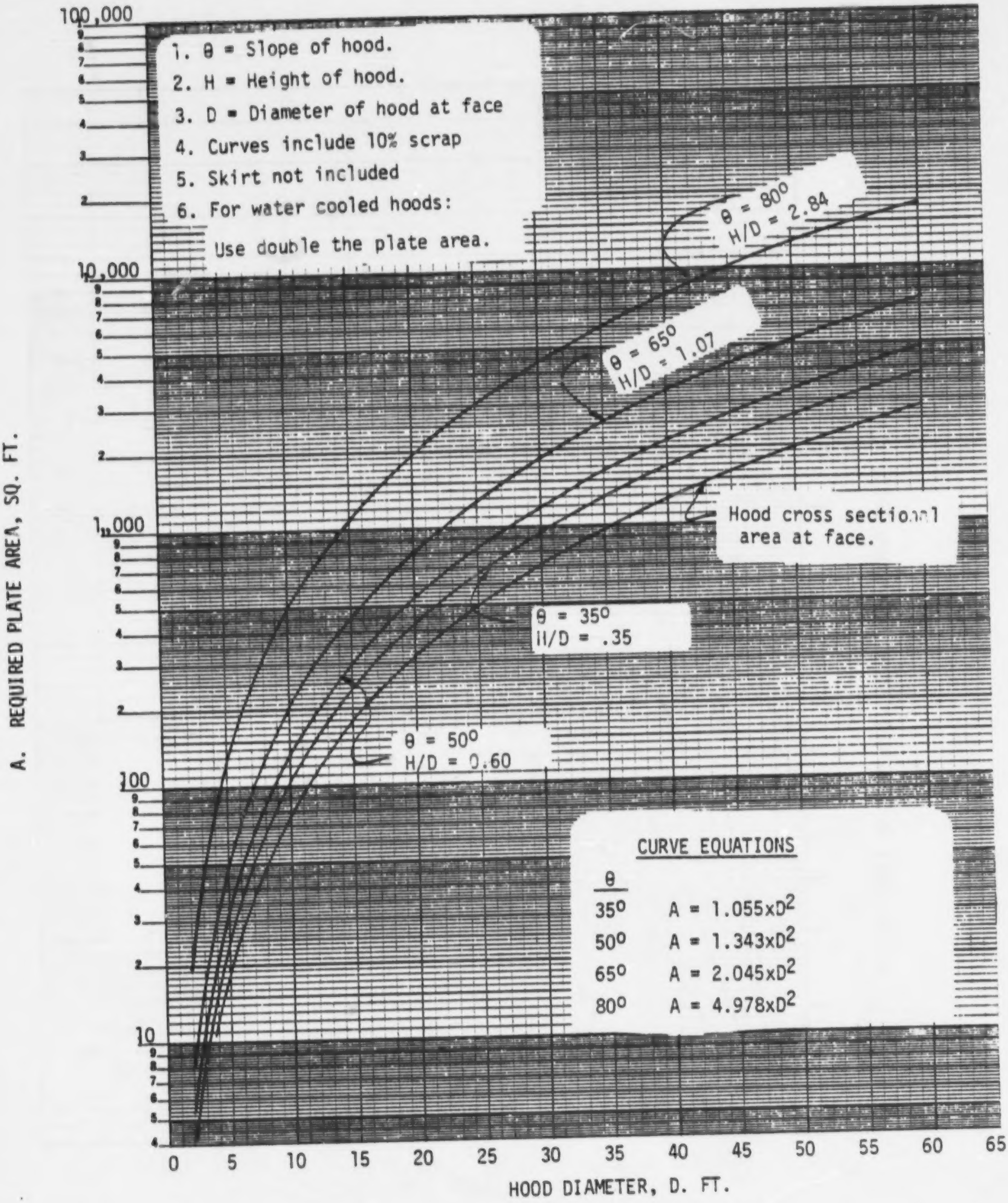
[*] To determine angle of slope, see Appendix C, ref. 129, Fan Engineering, especially Figure 57, p 114.



1. Slope of Hood = 35°
2. L = Lenth
3. W = Width
4. Curves Include 10% Scrap
5. Skirt Not Included
6. For Water Cooled Hoods Use Double - the Plate Area

L/W	CURVE EQUATIONS
1	$A = 12 + 2.84\ L^2$
2	$A = 4 + 1.25\ L^2$
4	$A = 1 + 0.615\ L^2$
8	$A = .5 + 0.306\ L^2$

Figure 4-3 RECTANGULAR CANOPY HOOD PLATE AREA REQUIREMENTS VS. HOOD LENGTH AND L/W



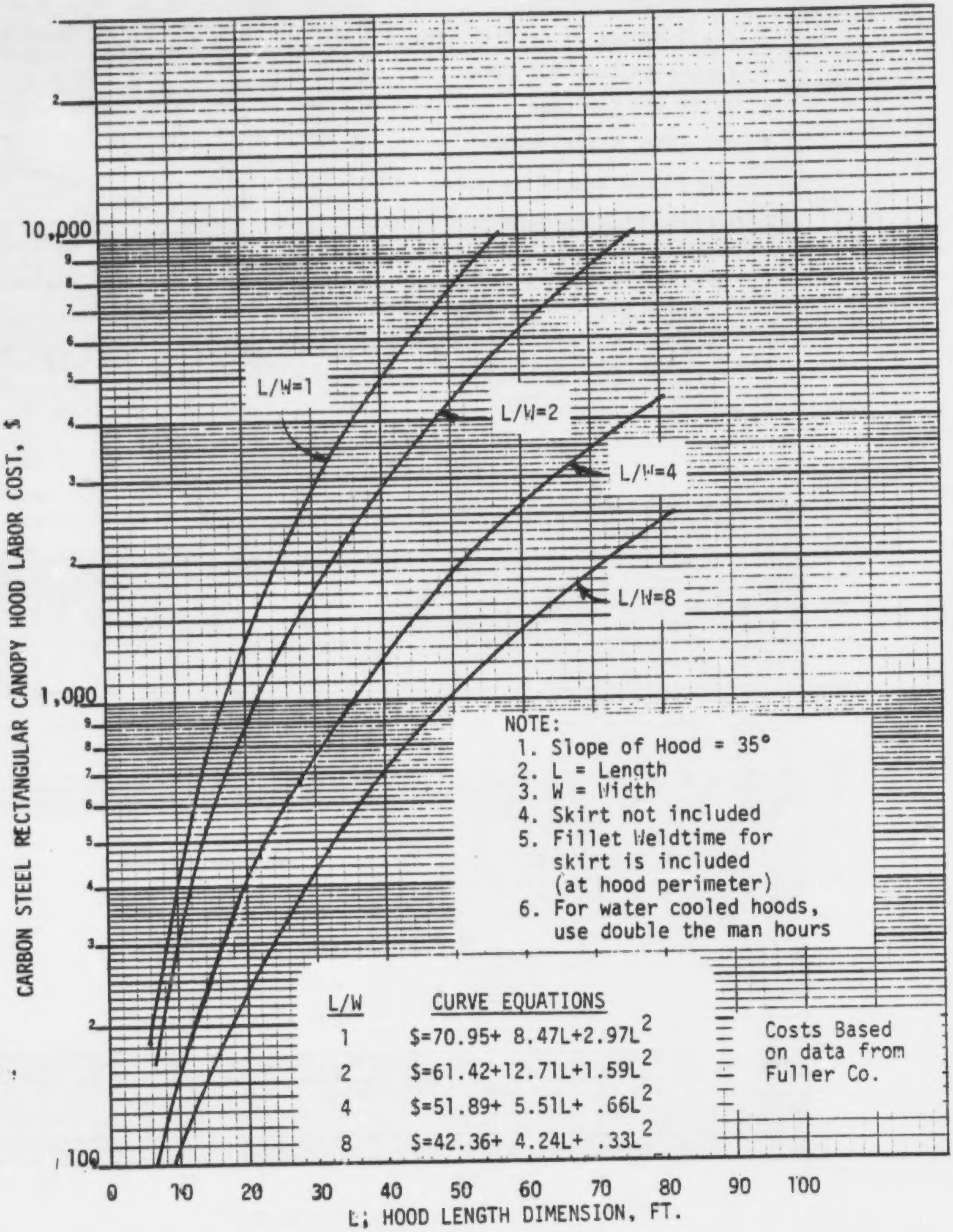
1. θ = Slope of hood.
2. H = Height of hood.
3. D = Diameter of hood at face
4. Curves include 10% scrap
5. Skirt not included
6. For water cooled hoods:

   Use double the plate area.

CURVE EQUATIONS

θ	
35°	$A = 1.055 \times D^2$
50°	$A = 1.343 \times D^2$
65°	$A = 2.045 \times D^2$
80°	$A = 4.978 \times D^2$

Figure 4-4 CIRCULAR HOODS PLATE REQUIREMENTS



NOTE:
1. Slope of Hood = 35°
2. L = Length
3. W = Width
4. Skirt not included
5. Fillet Weldtime for skirt is included (at hood perimeter)
6. For water cooled hoods, use double the man hours

L/W	CURVE EQUATIONS
1	$\$=70.95+8.47L+2.97L^2$
2	$\$=61.42+12.71L+1.59L^2$
4	$\$=51.89+5.51L+.66L^2$
8	$\$=42.36+4.24L+.33L^2$

Costs Based on data from Fuller Co.

Figure 4-5 LABOR COST FOR FABRICATED 10 GA. CARBON STEEL RECTANGULAR CANOPY HOODS

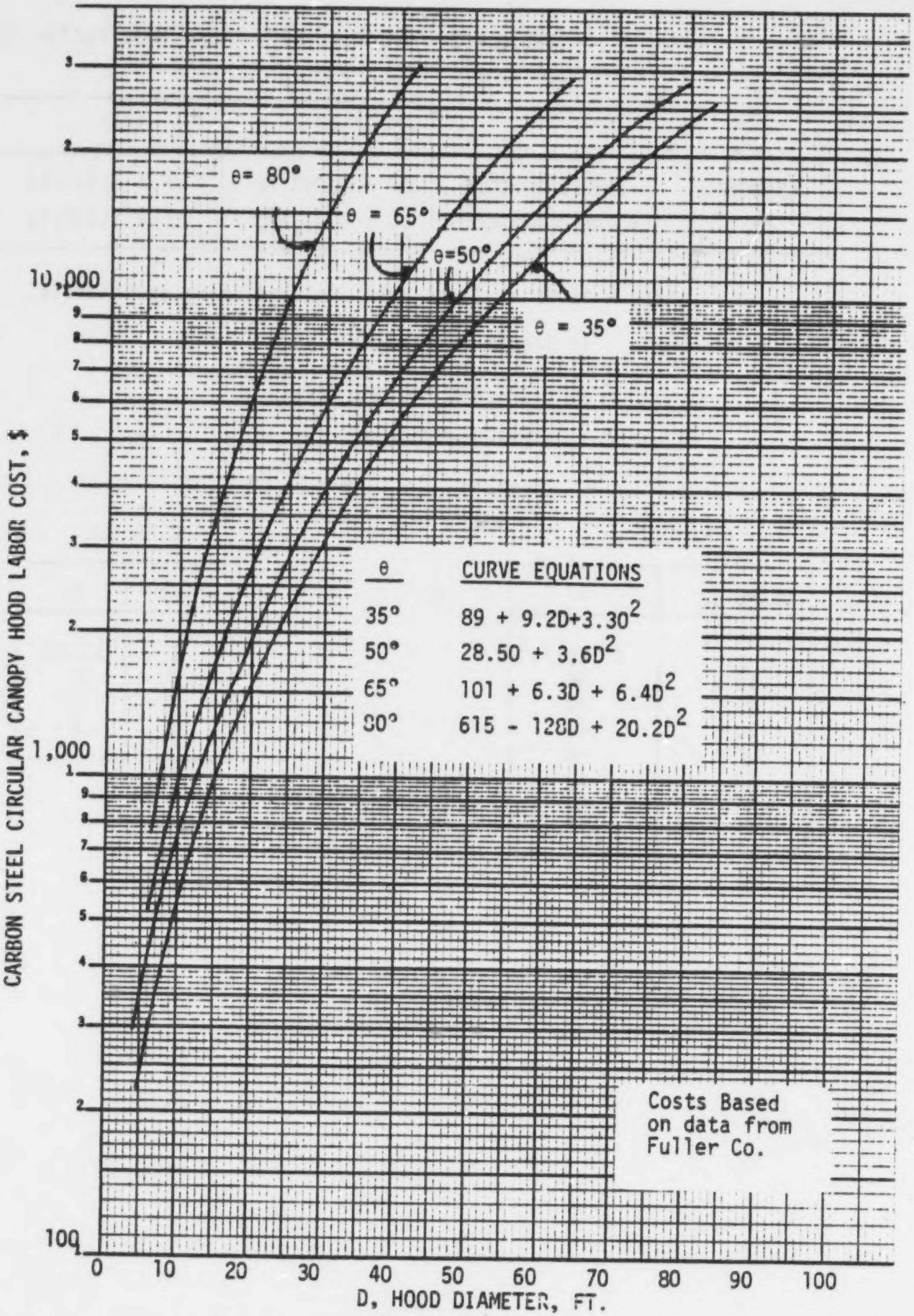


Figure 4-6 LABOR COST FOR FABRICATED 10 GA. CARBON STEEL CIRCULAR CANOPY HOODS

Table 4.2 MATERIAL COST (Ref. 160), Fuller Co.

		$\leq$ 3/16"	$\geq$ 1/4"
CARBON	CIRCULAR HOODS	AF + \$.243/lb	AF + \$.227/lb
STEEL	RECTANGULAR HOODS	LG + \$.243/lb	LG + \$.227/lb

where A is total plate area, not including structurals,

L is length of hood,

F is a pricing factor, and

G is a pricing factor.

F FACTOR

DIAMETER	F
5	\$ .90/ft^2
10	.60
15	.50
20	.45
30	.40
40	.40
50	.35
70	.35

G FACTOR

L/W	G
1	\$12/ft
2	8
4	4
8	2

Since 10 Ga. (.1382") is usually sufficient for hoods, the total mass of the hoods and structurals in the two examples is:

$$250\ \text{ft}^2 \times 5\ .625\ \text{lb/ft}^2 \times 1.2 = \sim 1690\ \text{lb}$$

$$550\ \text{ft}^2 \times 5.625\ \text{lb/ft}^2 \times 1.2 = \sim 3700\ \text{lb}$$

The material cost, cut to size, is estimate from Table 4.2.

Using these formulas, the material cost is calculated to be:

$$550\ \text{ft}^2 \times \$.45/\text{ft}^2 + \$.243/\text{lb} \times 3700\ \text{lb} = 1150$$

$$20\ \text{ft} \times \$4/\text{ft} + \$.243/\text{lb} \times 1690\ \text{lb} = 490$$

Hence the total price for the two examples is:

35° Rectangular Hood, 20' x 5': \$425 + \$490 = \$915

50° Circular Hood, 20' dia: \$2010 + \$1150 = \$3160

If skirts or booth walls are needed, figure material cost at \$.243/lb. The weight of the wall will be the plate area (summation of the length times width of each wall) times the material weight, plus 20% additional for structurals. For labor cost, figure cost at \$.30/lb.

4.2 Ducting

Ducting has several effects on the size and cost of a control system. In addition to conveying the pollutant-laden stream to the control device, the ductwork can act as a heat exchange means for cooling of hot gases. Also, it always adds flow resistance or pressure losses that require added horsepower for the fan.

The four basic types of ducting can be classified as carbon steel, stainless steel, water cooled, and refractory. The differentiation between types is not necessarily based on construction alone but rather on the capability of each to transport gases at different temperatures. Water-cooled and refractory ducts can convey gases at any temperature, but are economically used at gas temperatures above 1500°F. Stainless steel ducts are generally used with gas temperatures between 1150°F and 1500°F or where the corresponding wall temperature is below 1200°F. Carbon steel ducts are used at gas temperatures below 1150°F or where the wall temperature is less than 800°F. In the transfer of corrosive gases, stainless steel ducts can be used at lower temperatures. For cold processes, carbon steel ducts are used exclusively for non-corrosive gases.

In designing ducts, a savings in the size of the ducts (increasing velocity) will eventually be compensated for in fan horsepower, therefore, the design velocity of the gas stream is maintained at a suitable conveying velocity for the type of dust. Typical velocities for industrial dusts are listed as follows (Ref. 88):

DUST TYPE	DUCT VELOCITY, fpm
1) Light Density - gases, smokes, zinc and aluminum oxide fumes, flour, and lint	2000
2) Medium/Light Density - grain, sawdust, plastic and rubber dusts.	3000
3) Medium/Heavy Density - iron and steel furnace dusts, cement dusts, sandblast and grinding dusts, and most heavy industry dusts.	4000
4) Heavy Density - metal turnings, lead and foundry shakeout dusts.	5000

These velocities are presented as guidelines and have been developed from practical experience and data obtained from industrial applications. The minimum velocity that must be maintained to prevent dust from settling in a duct is determined from the following formulas.

$$V_h = 105 \left(\frac{SG}{SG+1}\right) d^{0.4}$$ (ref. 152)

where: V_h = horizontal duct velocity, fpm.

SG = specific gravity (relative to water at 60°F and 14.69 psia)

d = particle diameter, microns

$$V_v = 0.27\ V_h d^{0.2}$$ (ref. 152)

where: V_v = vertical duct velocity, fpm.

The diameter of a duct for a specific design velocity and gas flowrate is determined by:

$$D = 13.54 \sqrt{\frac{Q}{V}}$$

where: D = duct diameter, inches

Q = gas flowrate, cfm

V = duct velocity, fpm.

The formulas for determining the minimum duct velocity are based on experimental data using relatively large clean dust particles (1-5 millimeters in diameter). In most industrial gas streams, the particulate is a mixture of dusts inadequately identified as to size, configuration, and adhesive properties; thus, the formulas tend to predict lower minimum velocities than those recommended by industry. A more detailed discussion of this is contained in reference 152.

Since the types and configurations of ductwork are so varied, the cost of these items must be estimated according to size, type, materials of construction and plate thicknesses. For ducting, the costs are developed on a per lineal foot basis.

The cost of the ductwork for any application must include accessories normally associated with the conveyance of a gas stream. These include elbows, tees, expansion joints, dampers and transitions. The costs of these items are segregated from the cost of straight duct as shown in the following figures.

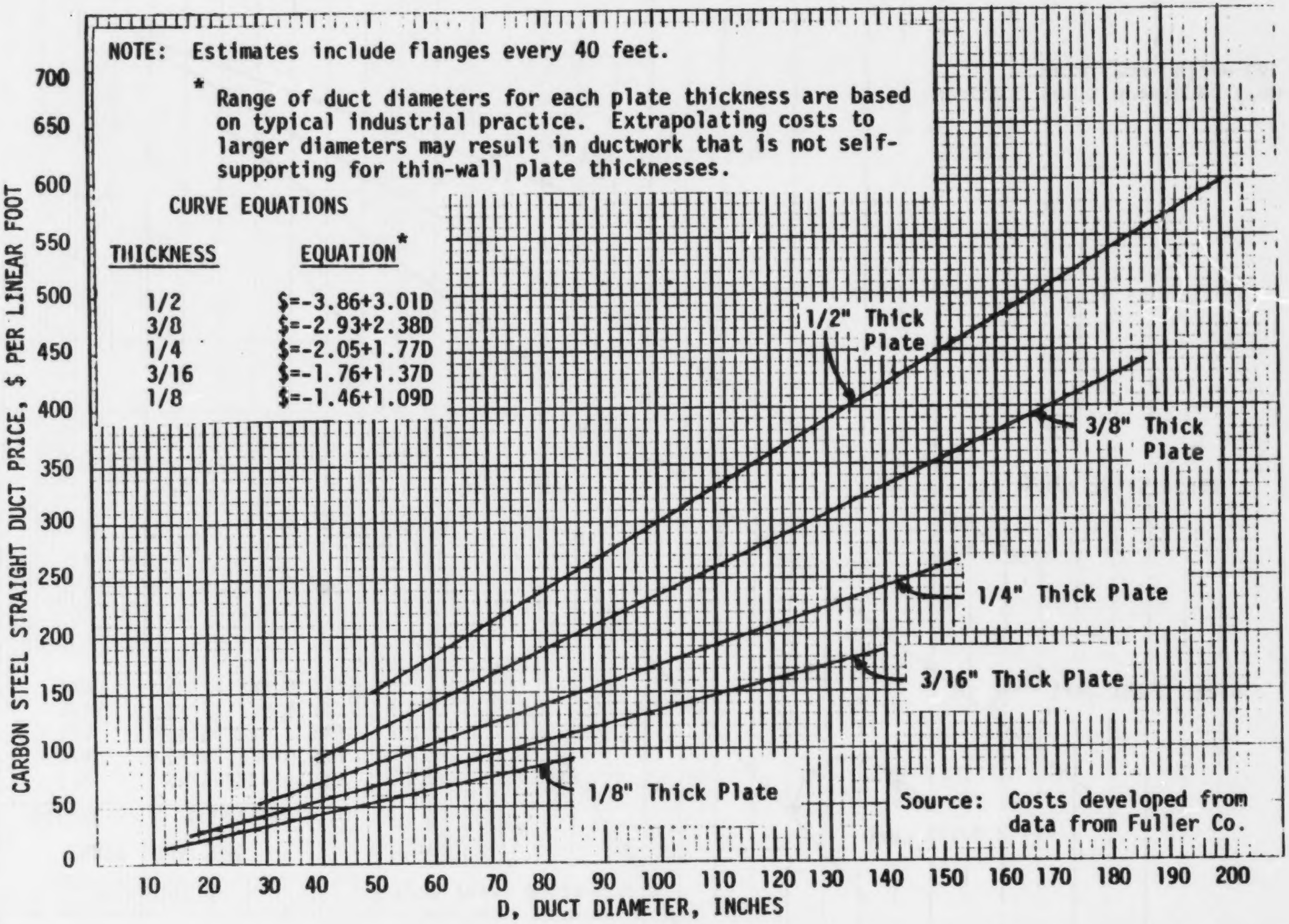
For straight duct sections, Figure 4-7 gives the price for fabricated carbon steel duct in dollars per foot as a function of duct diameter and material thickness. A 48-inch duct, 1/4-inch thick costs \$83/ft. Hence 100 ft costs \$8300. Figure 4-8 gives prices for stainless steel construction and Figure 4-9 gives prices for water cooled carbon steel duct.

Figures 4-10 and 4-11 contain prices for carbon steel and stainless steel elbow duct, respectively. Prices are a function of duct diameter and material thickness.

For tees, the price will be 1/3 the corresponding price of an elbow having the same diameter and thickness. For transitions, the price will be 1/2 the corresponding elbow price (use large diameter for sizing).

For expansion joints, Figure 4-12 contains prices for expansion joints as a function of duct diameter.

Table 4.3 contains pricing data for refractory materials. Refractory may be applied to capture hoods, straight duct, elbows, tees, transitions, spray chambers, thermal and catalytic incinerators (for replacement), and stacks. The thickness of the insulation for these applications depends on the thermal conductivity of the selected insulation, the temperature of the hot face (refractory skin temperature), and the required temperature of the cold face. The following values may be used as a guideline in determining the amount of insulation required when the temperature of the cold face is in a still air environment at 80°F (ref. 153).



NOTE: Estimates include flanges every 40 feet.

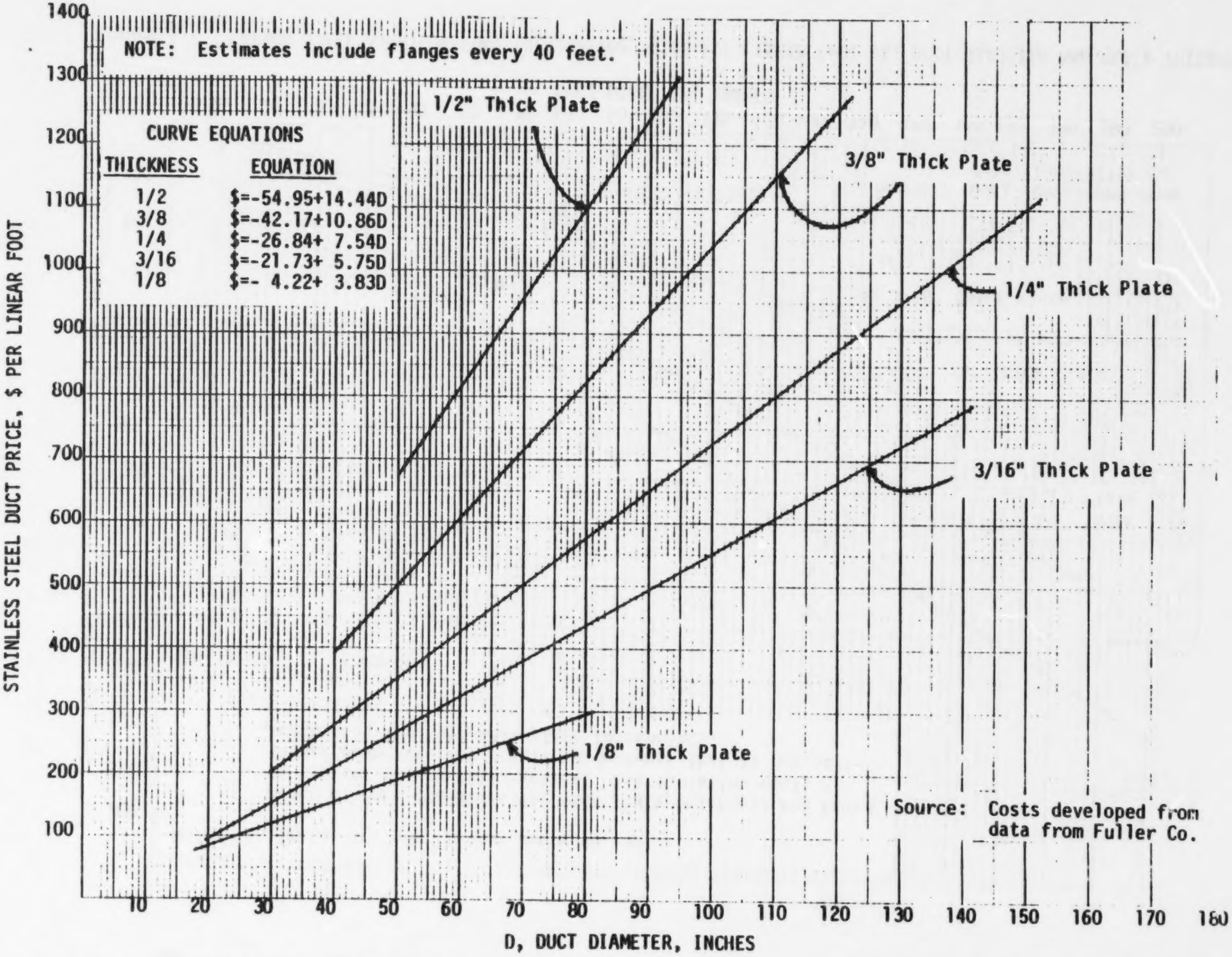
* Range of duct diameters for each plate thickness are based on typical industrial practice. Extrapolating costs to larger diameters may result in ductwork that is not self-supporting for thin-wall plate thicknesses.

CURVE EQUATIONS

THICKNESS	EQUATION*
1/2	$=-3.86+3.01D
3/8	$=-2.93+2.38D
1/4	$=-2.05+1.77D
3/16	$=-1.76+1.37D
1/8	$=-1.46+1.09D

Source: Costs developed from data from Fuller Co.

Figure 4-7 CARBON STEEL STRAIGHT DUCT FABRICATION PRICE PER LINEAR FOOT VS. DUCT DIAMETER AND PLATE THICKNESS



CURVE EQUATIONS

THICKNESS	EQUATION
1/2	$=-54.95+14.44D
3/8	$=-42.17+10.86D
1/4	$=-26.84+ 7.54D
3/16	$=-21.73+ 5.75D
1/8	$=- 4.22+ 3.83D

Source: Costs developed from data from Fuller Co.

Figure 4-8 STAINLESS STEEL STRAIGHT DUCT FABRICATION PRICE PER LINEAR FOOT VS. DUCT DIAMETER AND PLATE THICKNESS

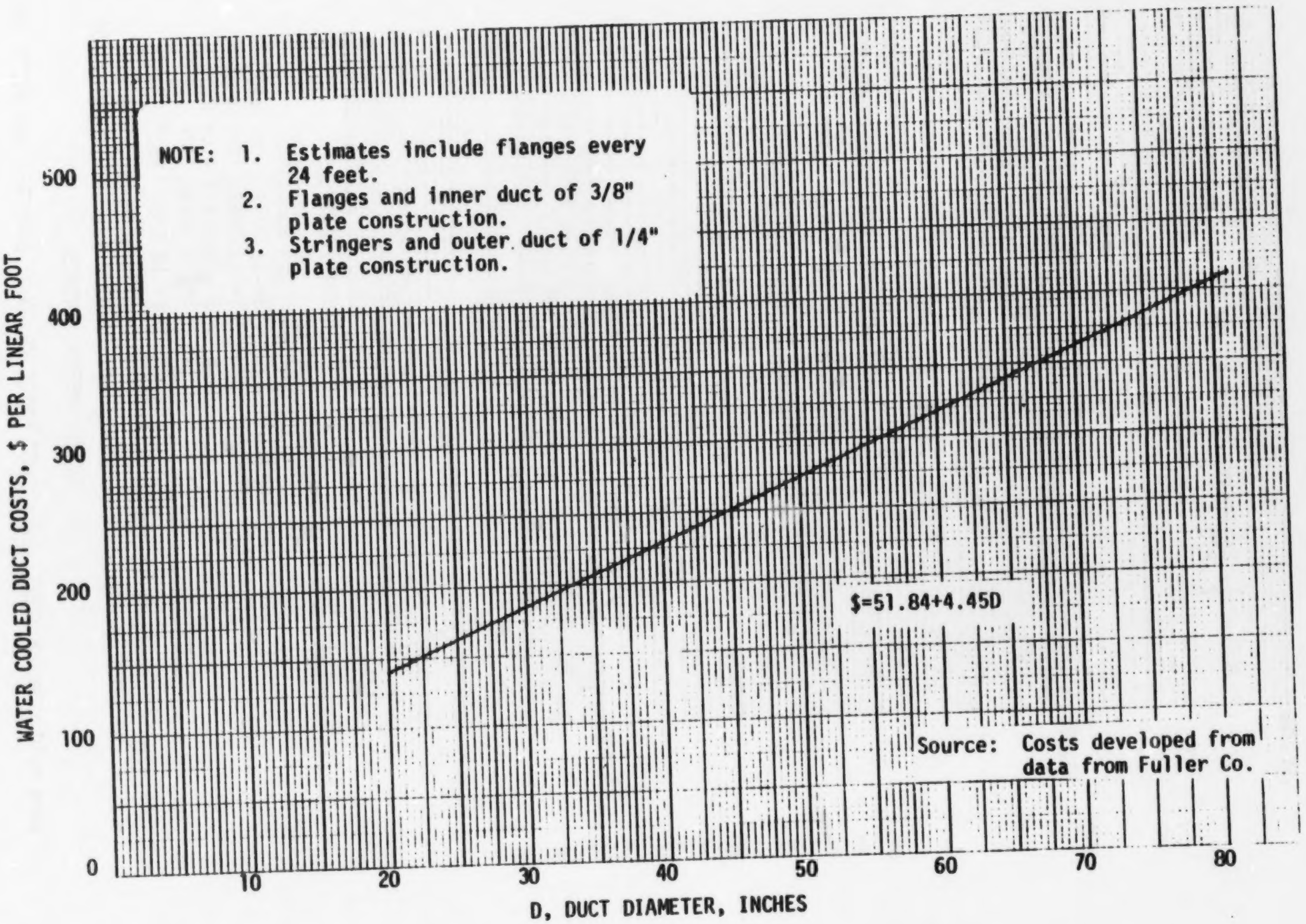
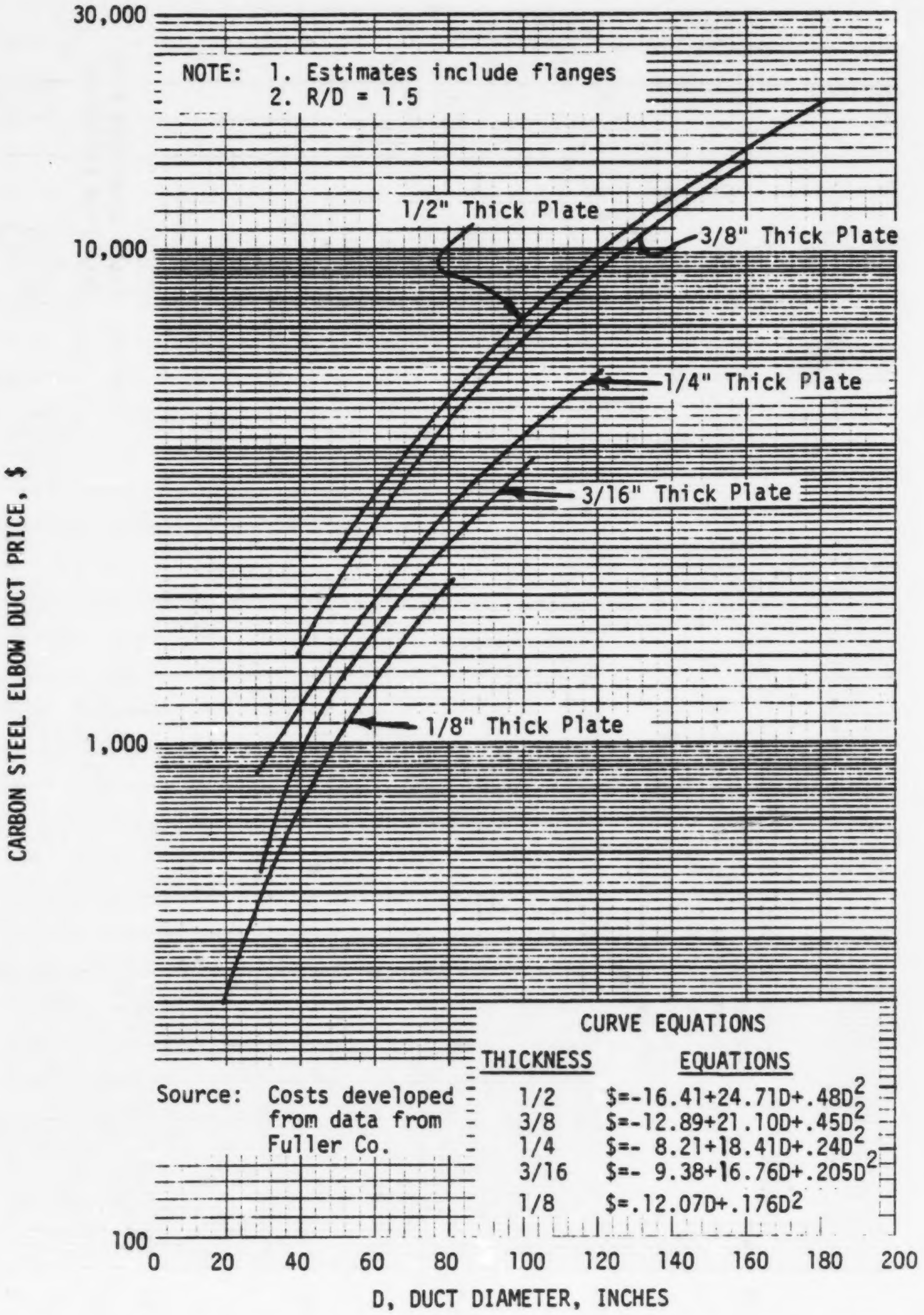


Figure 4-9 WATER COOLED CARBON STEEL STRAIGHT DUCT FABRICATION PRICE PER FOOT VS. DUCT DIAMETER



NOTE: 1. Estimates include flanges
2. R/D = 1.5

CURVE EQUATIONS

THICKNESS	EQUATIONS
1/2	$\$=-16.41+24.71D+.48D^2$
3/8	$\$=-12.89+21.10D+.45D^2$
1/4	$\$=-\ 8.21+18.41D+.24D^2$
3/16	$\$=-\ 9.38+16.76D+.205D^2$
1/8	$\$=.12.07D+.176D^2$

Source: Costs developed from data from Fuller Co.

Figure 4-10 CARBON STEEL ELBOW DUCT PRICE VS. DUCT DIAMETER AND PLATE THICKNESS

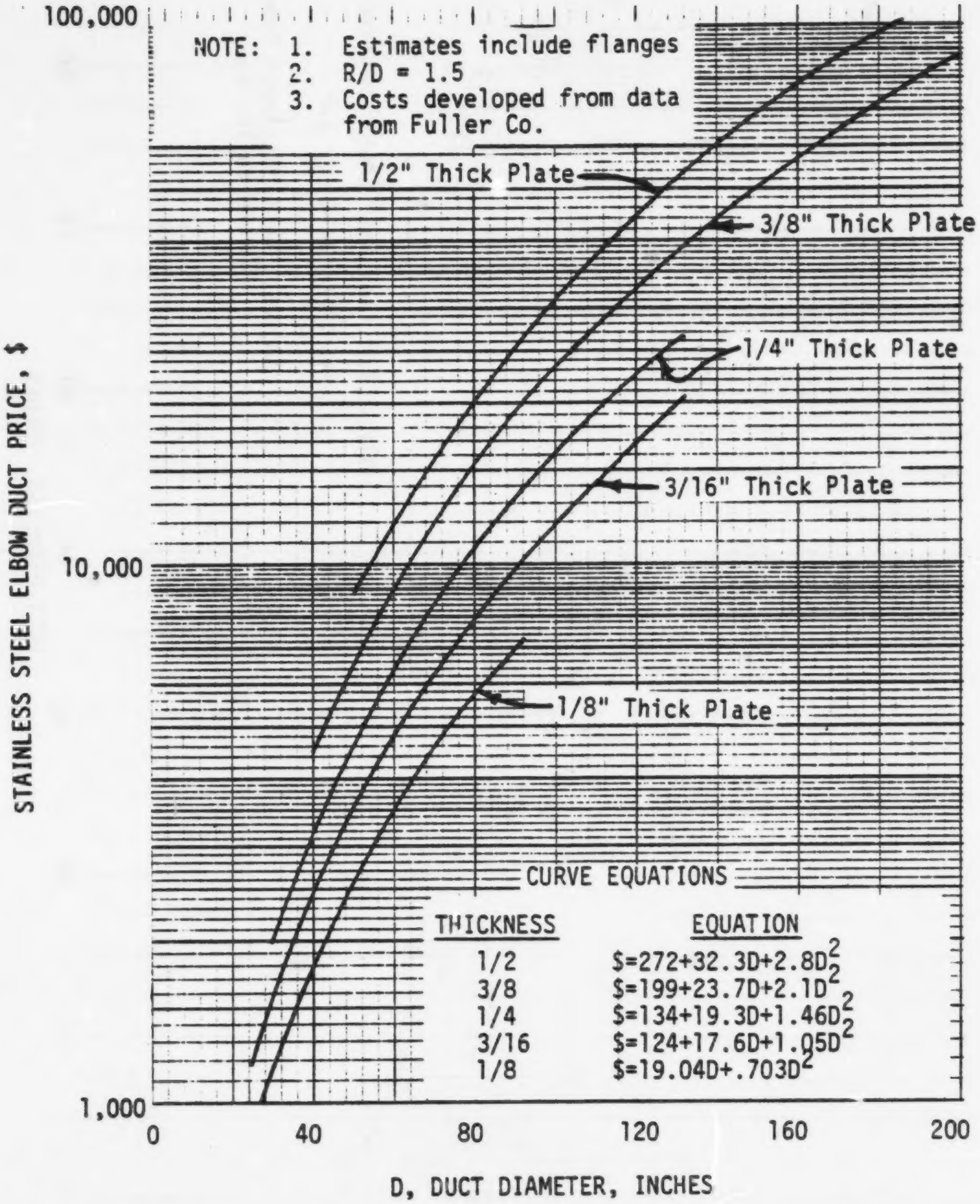
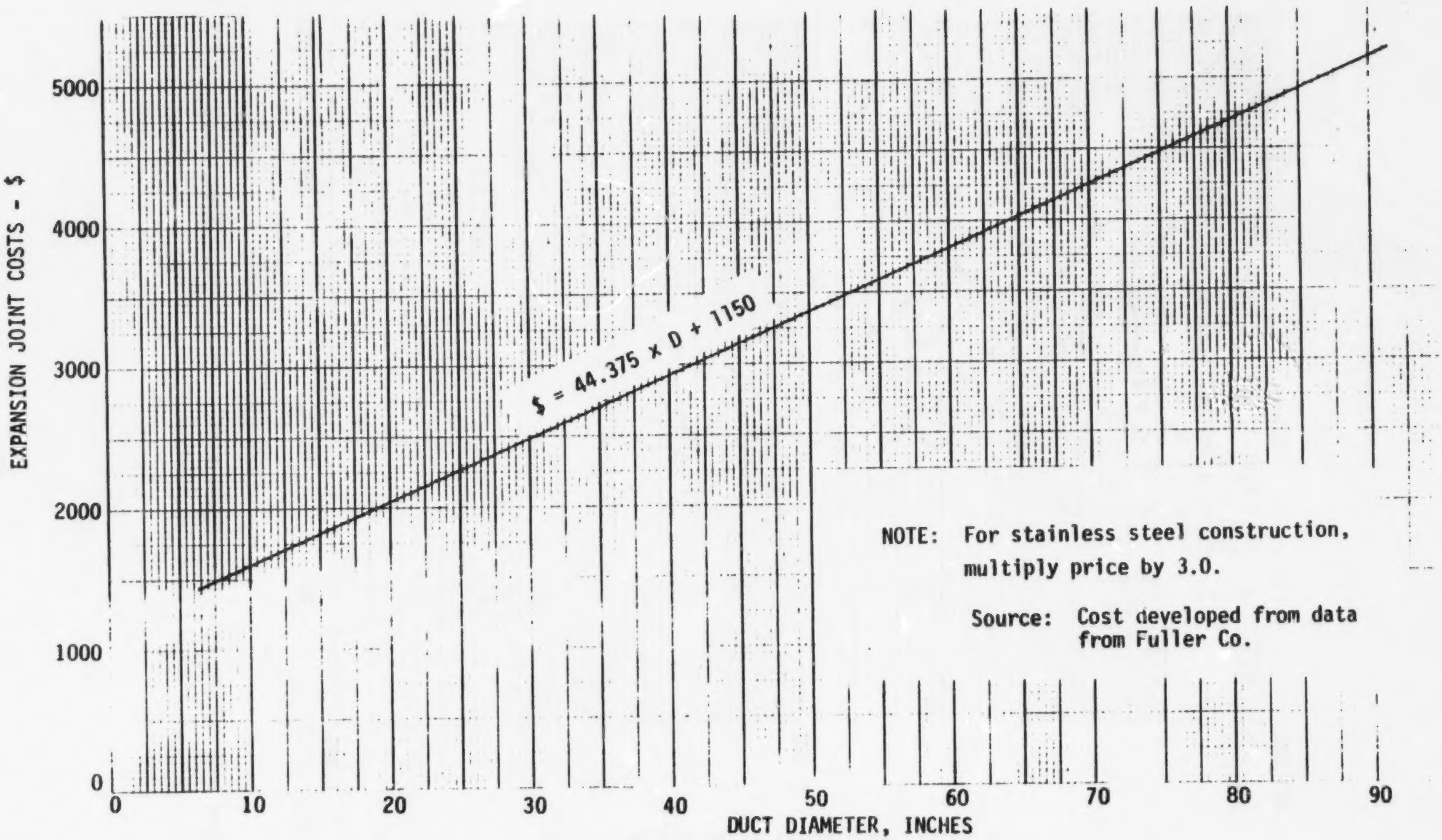


Figure 4-11 STAINLESS STEEL ELBOW DUCT PRICE VS. DUCT DIAMETER AND PLATE THICKNESS



NOTE: For stainless steel construction, multiply price by 3.0.

Source: Cost developed from data from Fuller Co.

Figure 4-12 CARBON STEEL EXPANSION JOINT COSTS VERSUS DUCT DIAMETER

TABLE 4.3

REFRACTORY ESTIMATING COSTS

TYPE	APPLICATION/FORM	THERMAL CONDUCTIVITY (Btu/hr.-ft^2.°F/in.) @		PURCHASED PRICE ($/cu. ft.)	INSTALLED COST ($/cu. ft.)
		1000°F	2000°F		
Super Duty Firebrick, 3200°F	Brick	9.3	10.0	$ 7	$90
Insulating Castable, 2000°F	Cast in Forms, Trowelled, or Gunned	1.9	2.1	$ 6	$30
Dense Castable, 3000°F	"	5.1	5.7	$25	$75
Plastic, 3000°F	Rammed w/Pneumatic Hammer	N/A	N/A	$13	N/A
Ceramic Fibre Matt, 2300°F	Like Mineral Wool	N/A	N/A	N/A	$25

N/A = Not Available.

Data based on ref. 37.

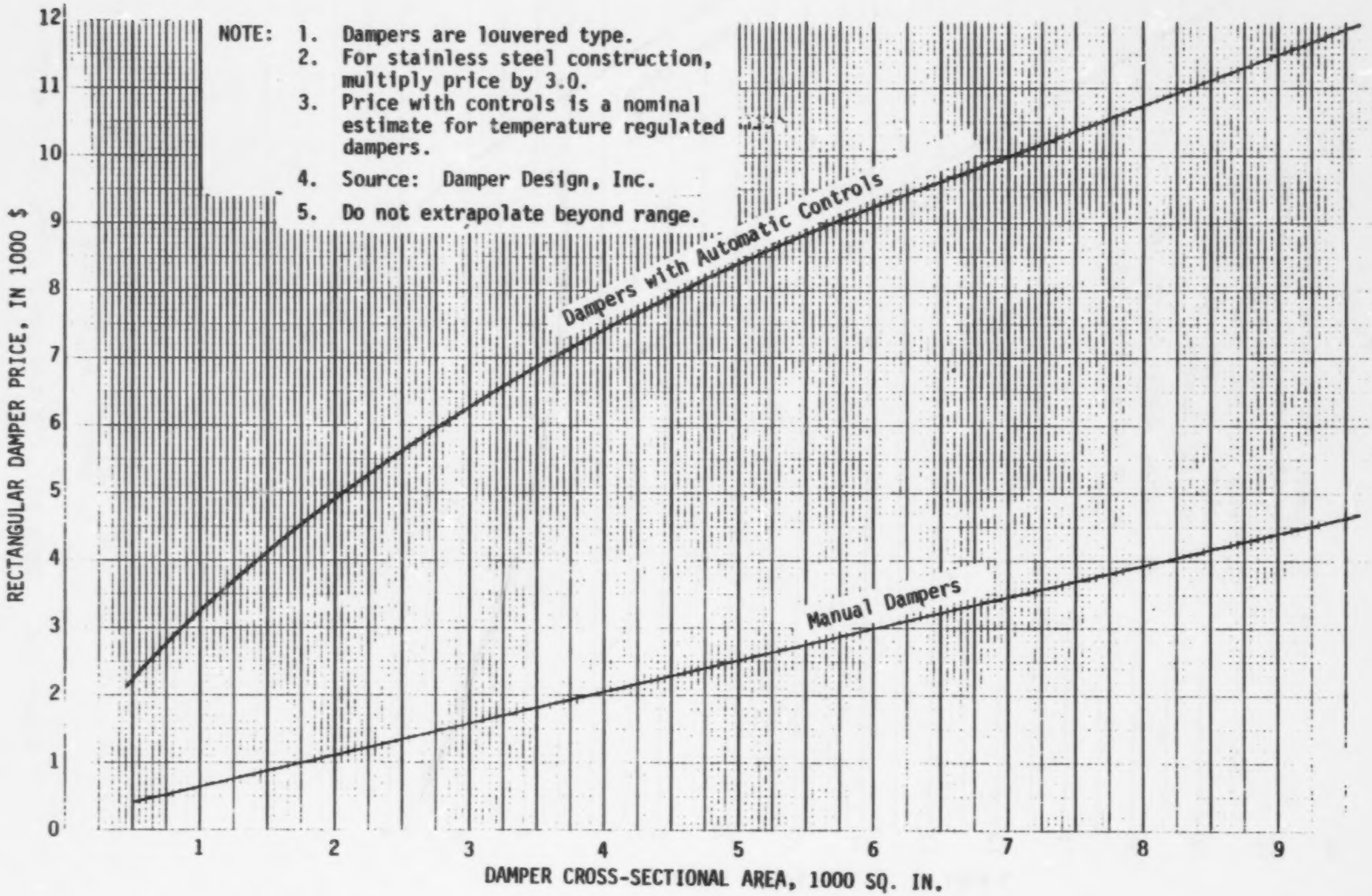
Hot Face Temperature (°F)	Cold Face Temperature (°F)	L/K*
1000	200	2.7
	300	1.1
	400	0.6
1500	200	4.5
	300	1.8
	400	1.0
2000	200	6.0
	300	2.6
	400	1.5

*where: L = Insulation thickness, inches

K = Thermal Conductivity, Btu/hr-ft^2-°F/inch (obtained from Table 4.3).

To estimate the cost, determine the surface area to be lined, the thickness of the lining, and the type of refractory to be used. Compute the cubic feet of refractory required and multiply by the price obtained from Table 4.3.

Prices for rectangular and circular dampers, with and without automatic temperature regulated controls, are contained in Figures 4-13 and 4-14, respectively. Rectangular dampers are priced as a function of cross-sectional area for length-to-width (L/W) ratios of 1.0 to 1.3. Circular dampers are priced as a function of damper diameter. These prices are for dampers only; the type that may be used inside a duct.



NOTE:
1. Dampers are louvered type.
2. For stainless steel construction, multiply price by 3.0.
3. Price with controls is a nominal estimate for temperature regulated dampers.
4. Source: Damper Design, Inc.
5. Do not extrapolate beyond range.

Figure 4-13 CARBON STEEL RECTANGULAR DAMPER PRICES VS. AREA

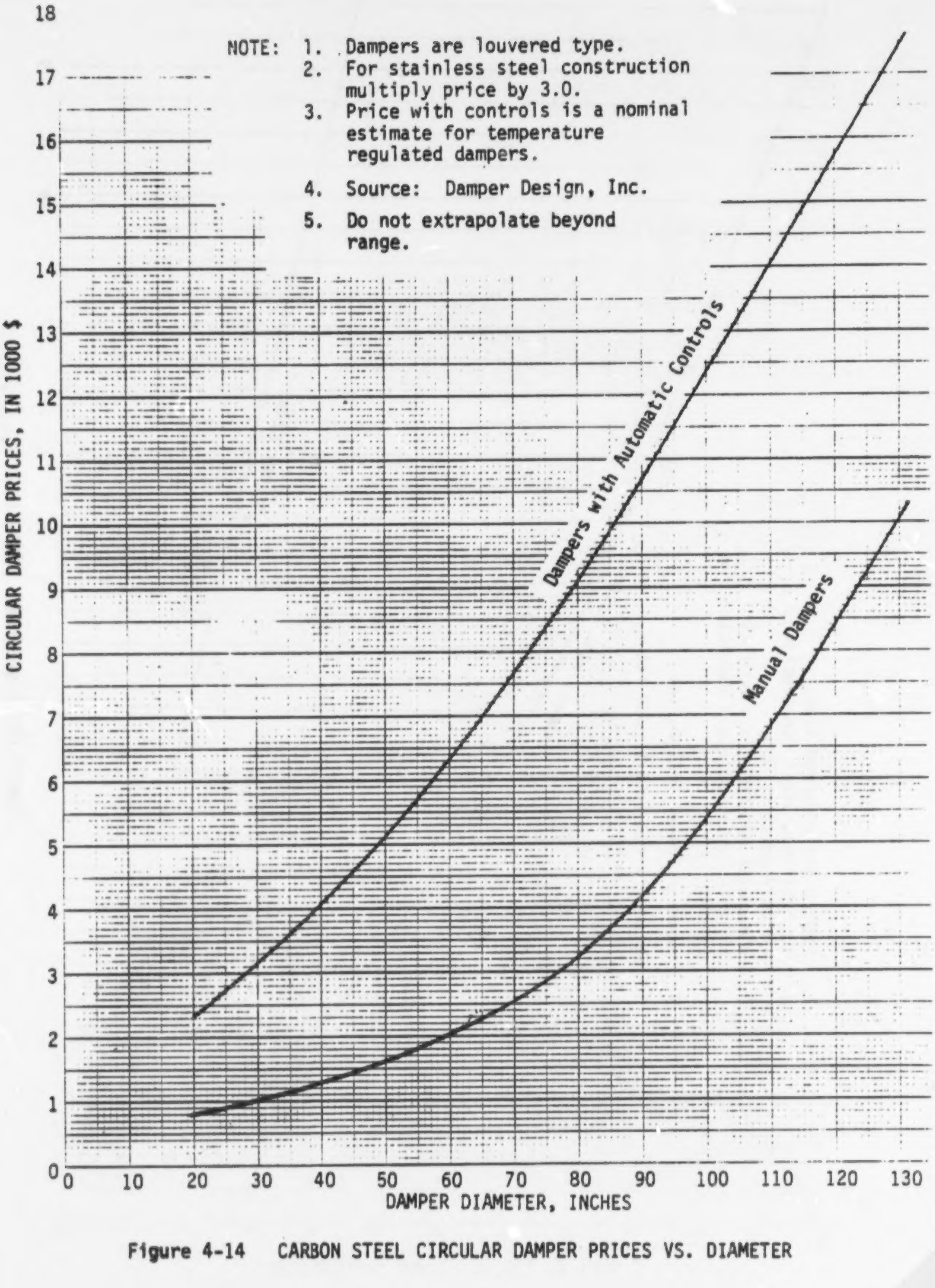

NOTE:
1. Dampers are louvered type.
2. For stainless steel construction multiply price by 3.0.
3. Price with controls is a nominal estimate for temperature regulated dampers.
4. Source: Damper Design, Inc.
5. Do not extrapolate beyond range.

Figure 4-14 CARBON STEEL CIRCULAR DAMPER PRICES VS. DIAMETER

4.3 Gas Conditioning

Gas conditioning equipment includes those components which precondition the gas stream prior to the control device. This equipment consists of mechanical collectors, wet or dry coolers, dilution devices, etc., which are used to temper or process the gas stream to provide the most efficient and economical operation of the control device.

Mechanical collectors, such as cyclones, are used in some cases as precleaners to remove the bulk of the heavier dust particles. These devices operate by separating the dust particles from the gas stream through the use of centrifugal force. Construction is such that centrifugal force is exerted on the gas stream through the use of a tangential inlet, producing a downward vortex. The particles impinge on the sides of the cyclone and are removed from the bottom. The gas stream changes direction at the base of the cyclone and exits in an upward vortex through an axial outlet at the top of the cyclone. Cyclones are available as large diameter conventional cyclones or as units having small multiple tubes for higher efficiencies. The efficiency of a cyclone collector is determined by the entering gas velocity and diameter at the cyclone inlet. Theoretically, the higher the velocity or the smaller the diameter, the greater the efficiency and pressure drop. All of these parameters can be correlated to the collector inlet area to establish the size and ultimately the cost of conventional cyclones.

Multiple tube cyclones are designed for high efficiencies and are normally used as a primary control device rather than as precleaners. These devices consist of banks of tubes, nine inches in diameter or less, and provide efficiencies of up to 80 percent for particle sizes of approximately 5 microns (ref. 154). The cost of these units is estimated to be $1.00 per cfm for capacities of up to 1000 cfm, $0.60 per cfm for 5000 cfm, and $0.50 per cfm for capacities of 10,000 cfm or greater (ref. 154).

For the purpose of precleaning, conventional cyclones can remove the majority of dust particles above 20-30 microns in size to reduce the loading and wear on the primary control device. Figure 4-15 provides a means of estimating the volume capacity of mechanical collectors (conventional cyclones) as a function of inlet cross-sectional area. Figure 4-16 provides a means of estimating the critical particle size for collectors vs. inlet area. Critical particle size is defined as the largest sized particle not separated from the gas stream. A guide to estimating cyclone shell thickness and pressure drop can be obtained in references 154 and 169.

Figures 4-17 through 4-21 contain pricing data for mechanical collectors and components as a function of inlet area.

For example, suppose 50,000 cfm is to be passed through a mechanical collector prior to entering a baghouse. A pair of 25,000 cfm capacity collectors with a pressure drop of 4" ΔP and an inlet area of 9-1/2 sq. ft. would be satisfactory for the purpose. The critical particle size is found to be 28 microns. For 10 Ga. carbon steel construction, the price of the collector would be about $5100. The cost of additional components would be:

support:	$3100
hopper:	880
*scroll:	1600
	$5580

The total price per collector is thus $5100 + 5580 = 10680. In general, price of collectors varies directly with inlet area since the mass of the unit increases with increasing area. However, these curves give prices for only single-unit collectors. Multiple collectors in parallel can be used for high

---

* Ductwork at outlet of cyclone to direct flow to horizontal ducting.

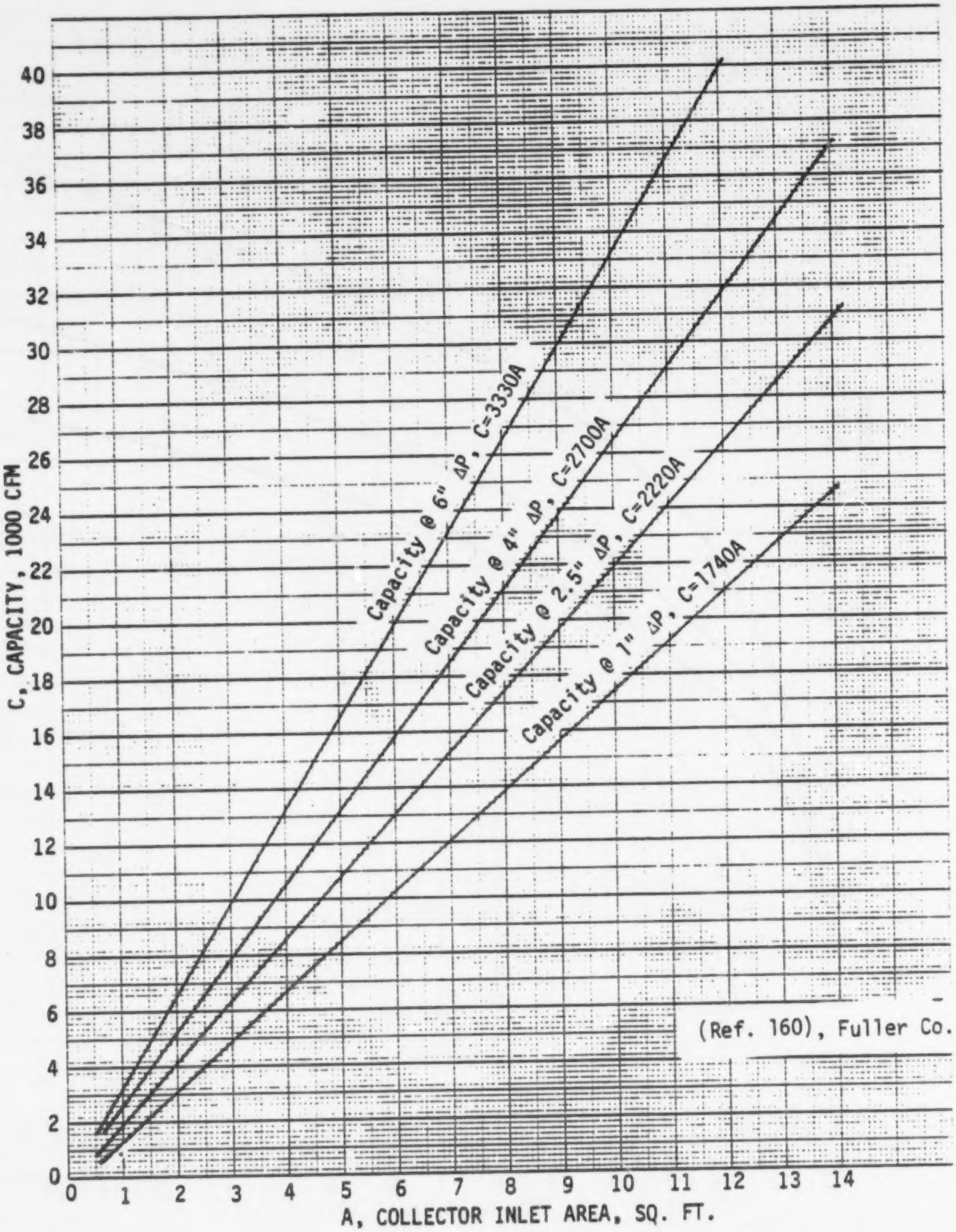


Figure 4-15 CAPACITY ESTIMATES FOR MECHANICAL COLLECTORS

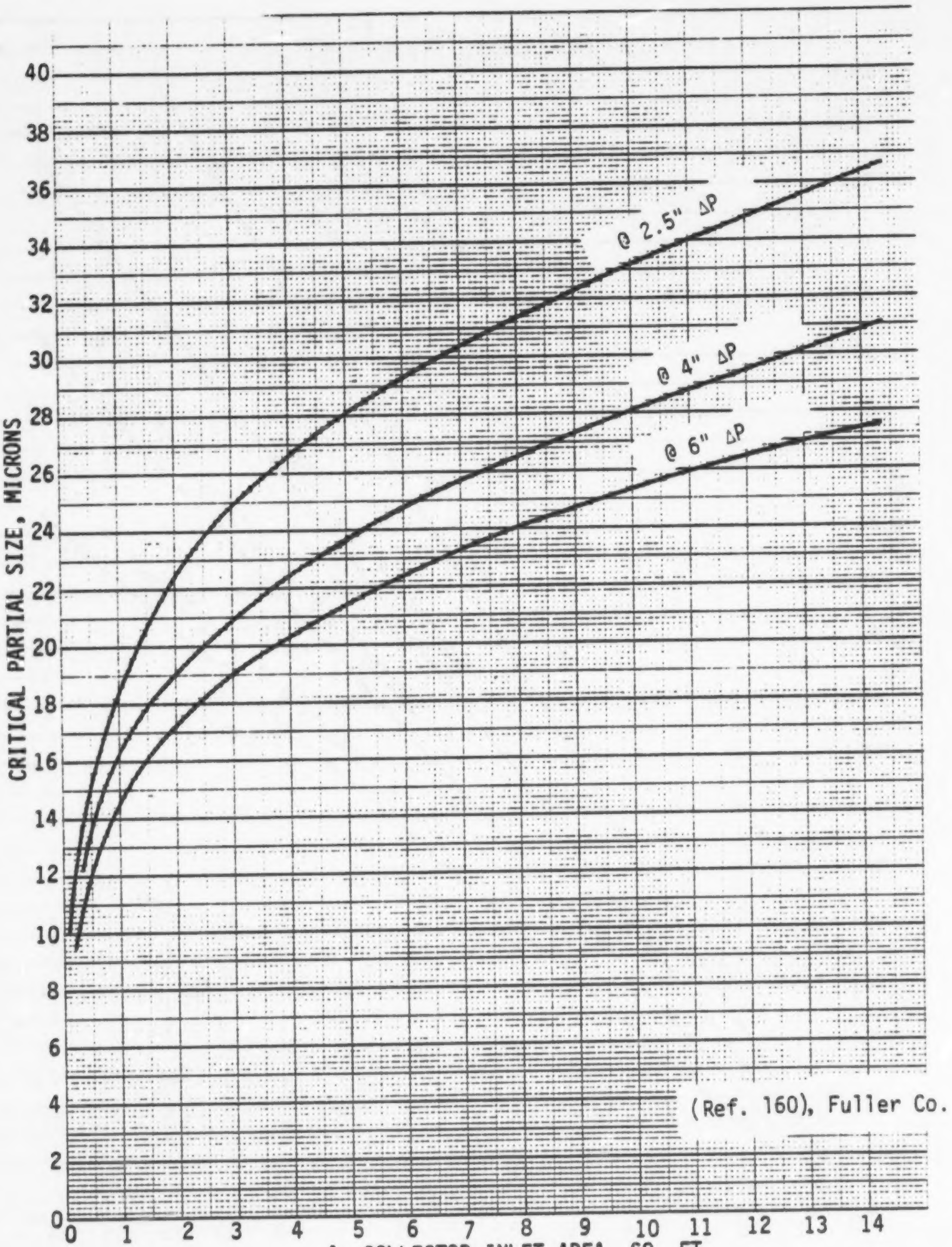


Figure 4-16 CRITICAL PARTIAL SIZE ESTIMATES FOR MECHANICAL COLLECTORS

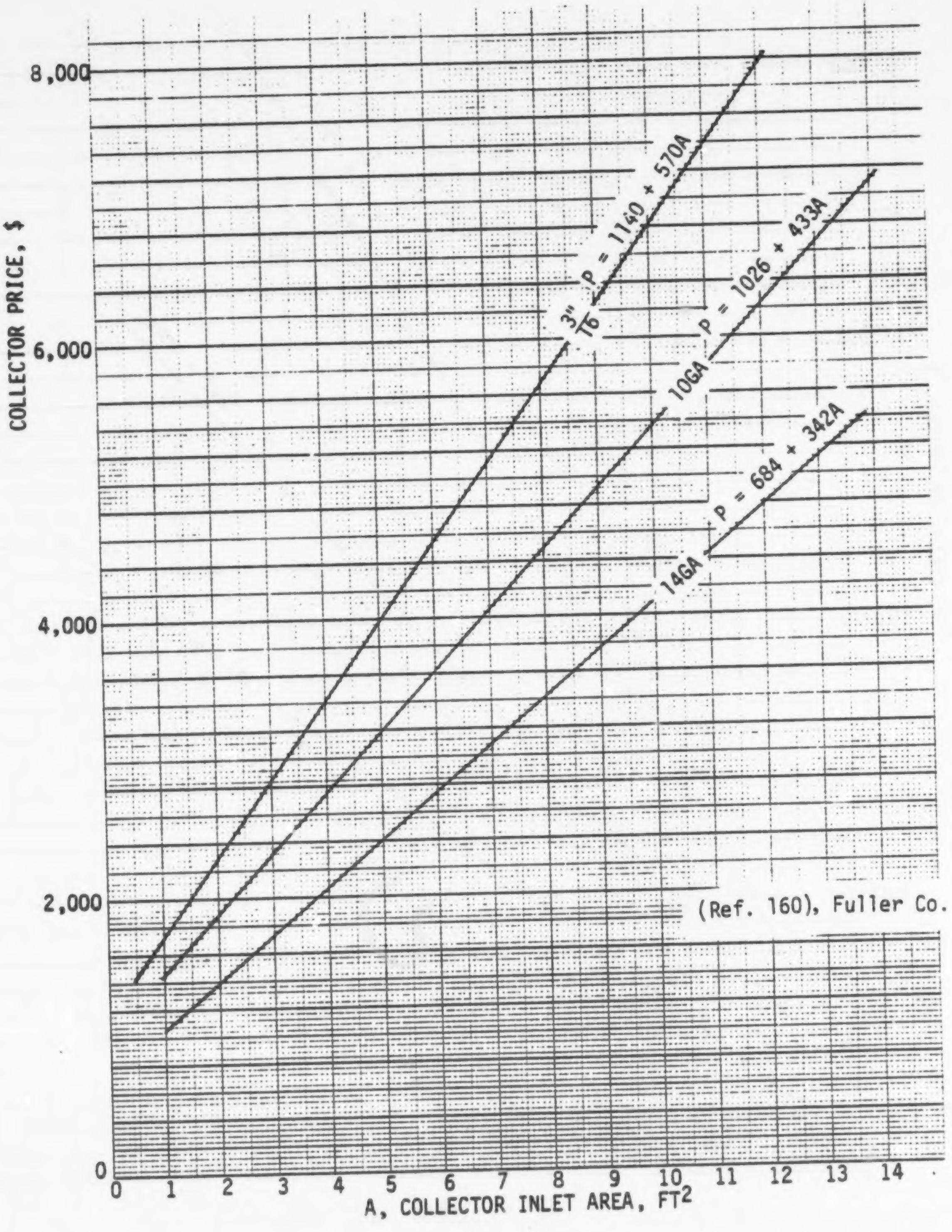
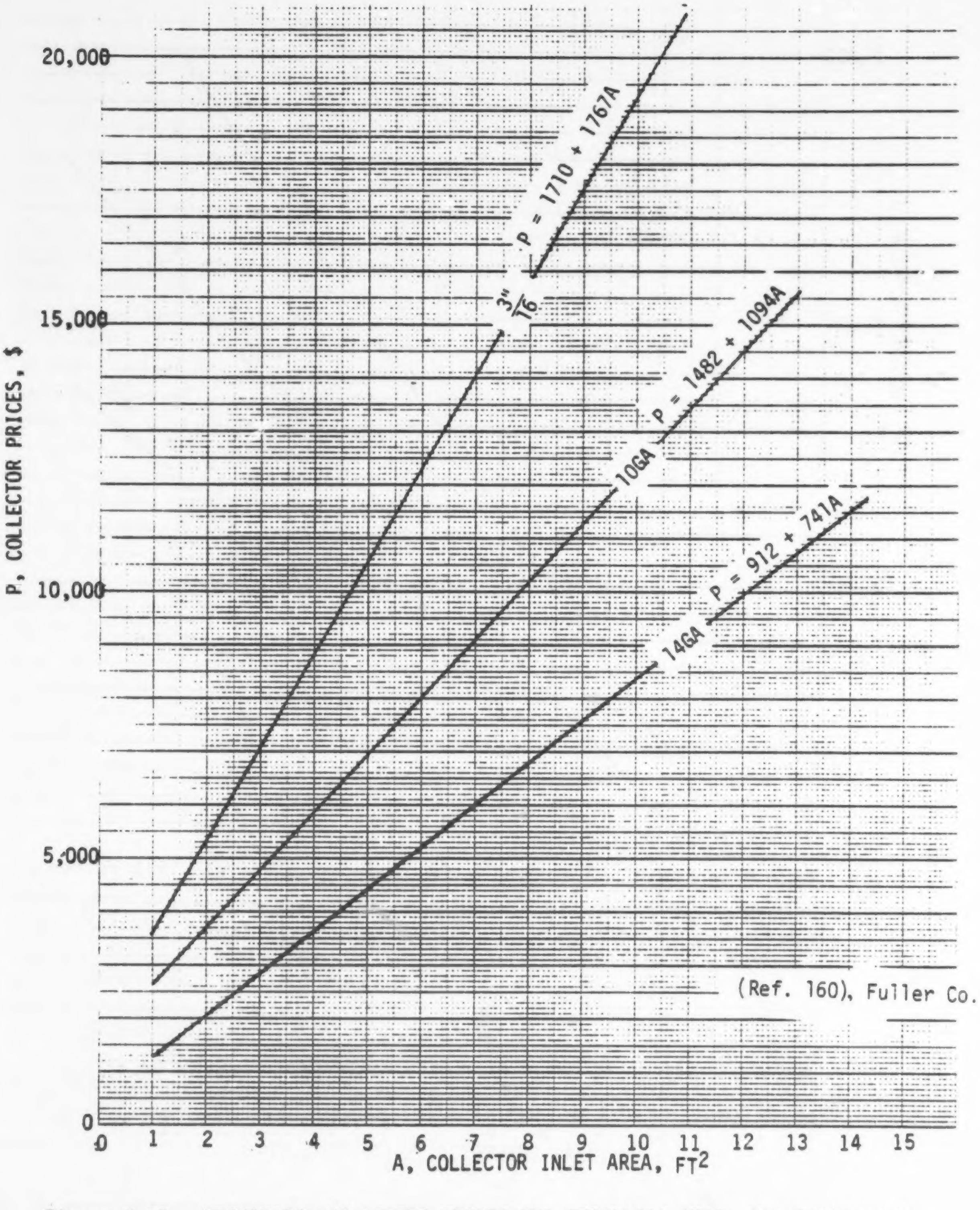


Figure 4-17 MECHANICAL COLLECTOR PRICES FOR CARBON STEEL CONSTRUCTION VS. INLET AREA



(Ref. 160), Fuller Co.

Figure 4-18 MECHANICAL COLLECTOR PRICES FOR STAINLESS STEEL CONSTRUCTION VS. INLET AREA

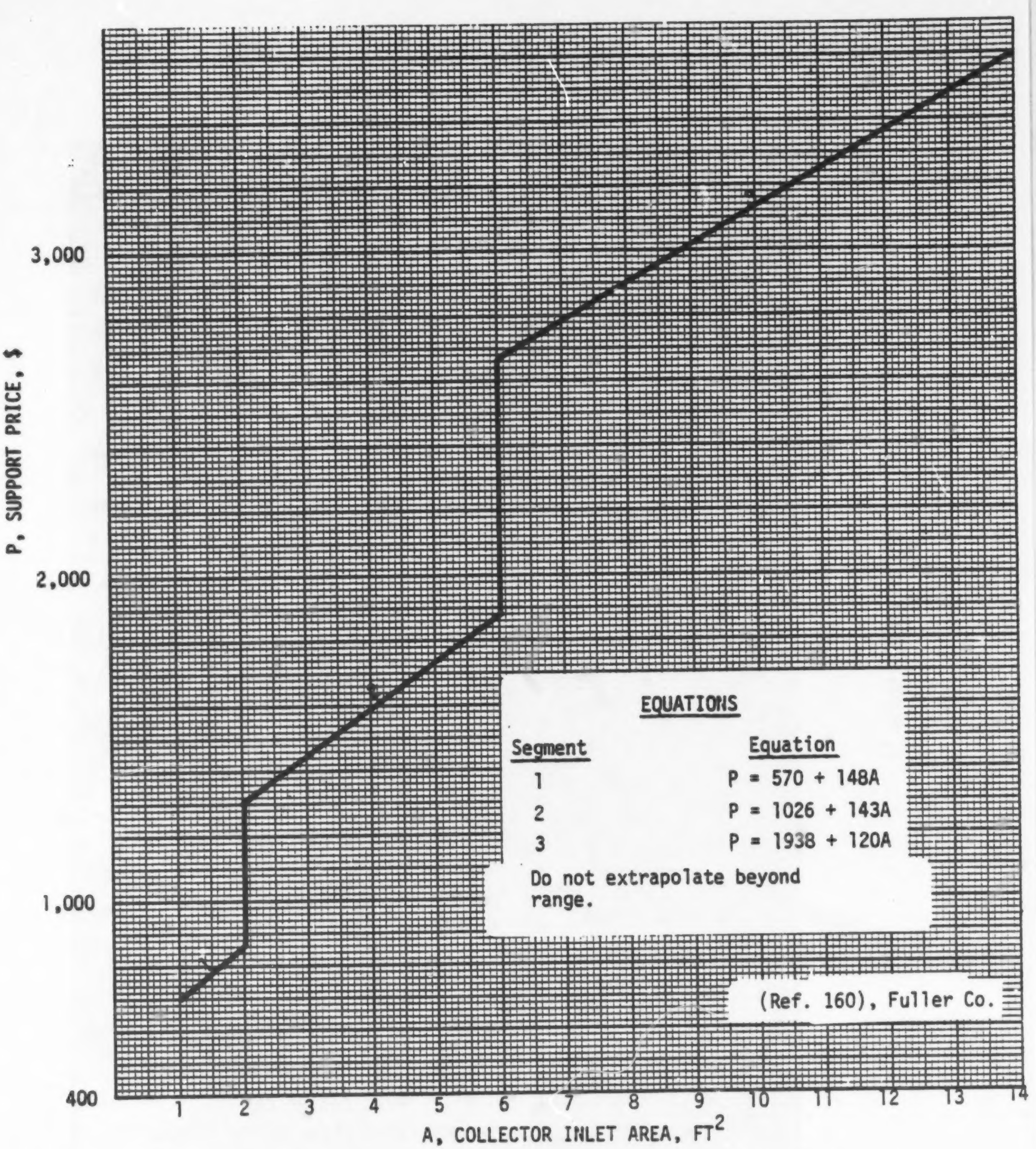


Figure 4-19 MECHANICAL COLLECTOR SUPPORT PRICES VS. COLLECTOR INLET AREA

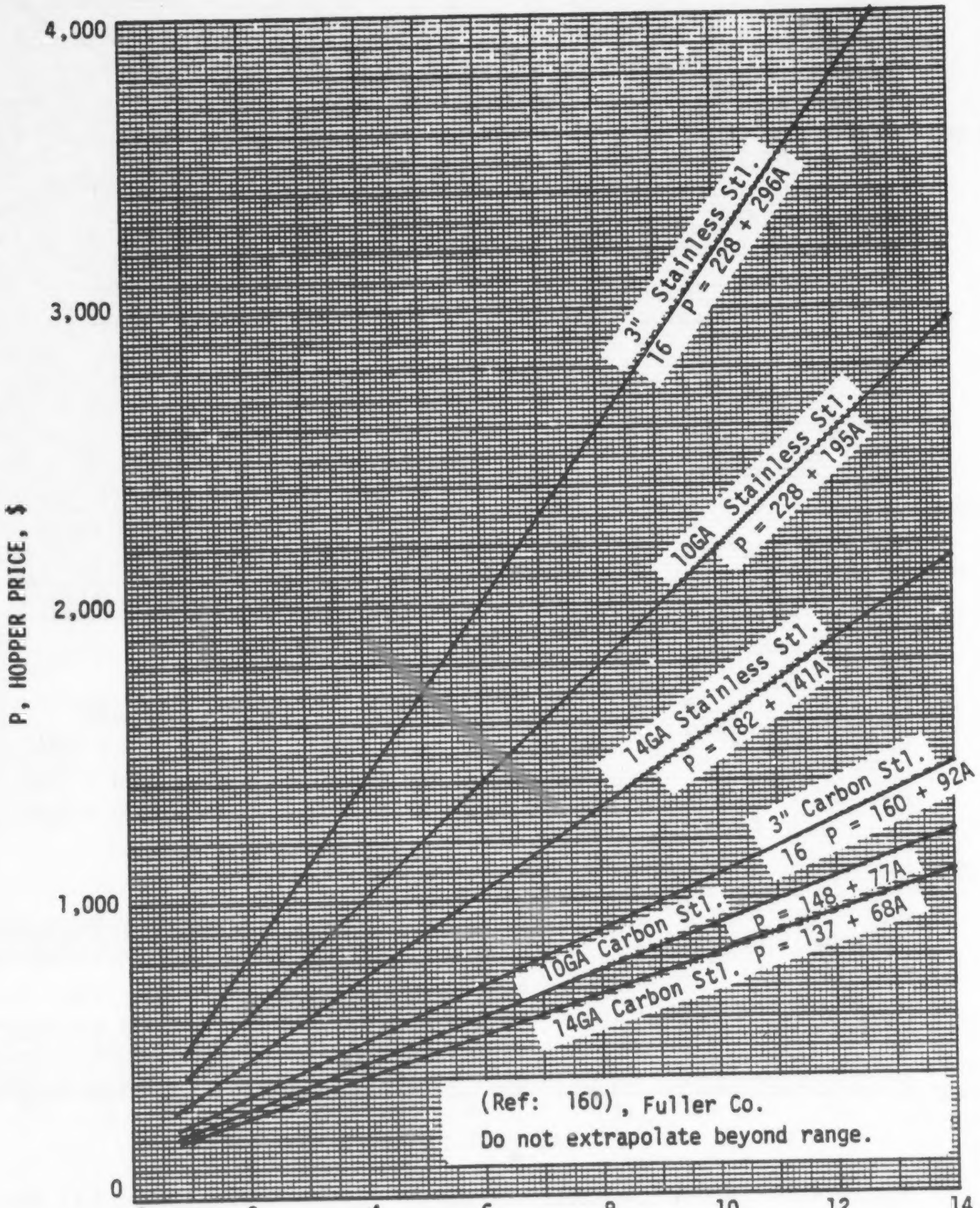
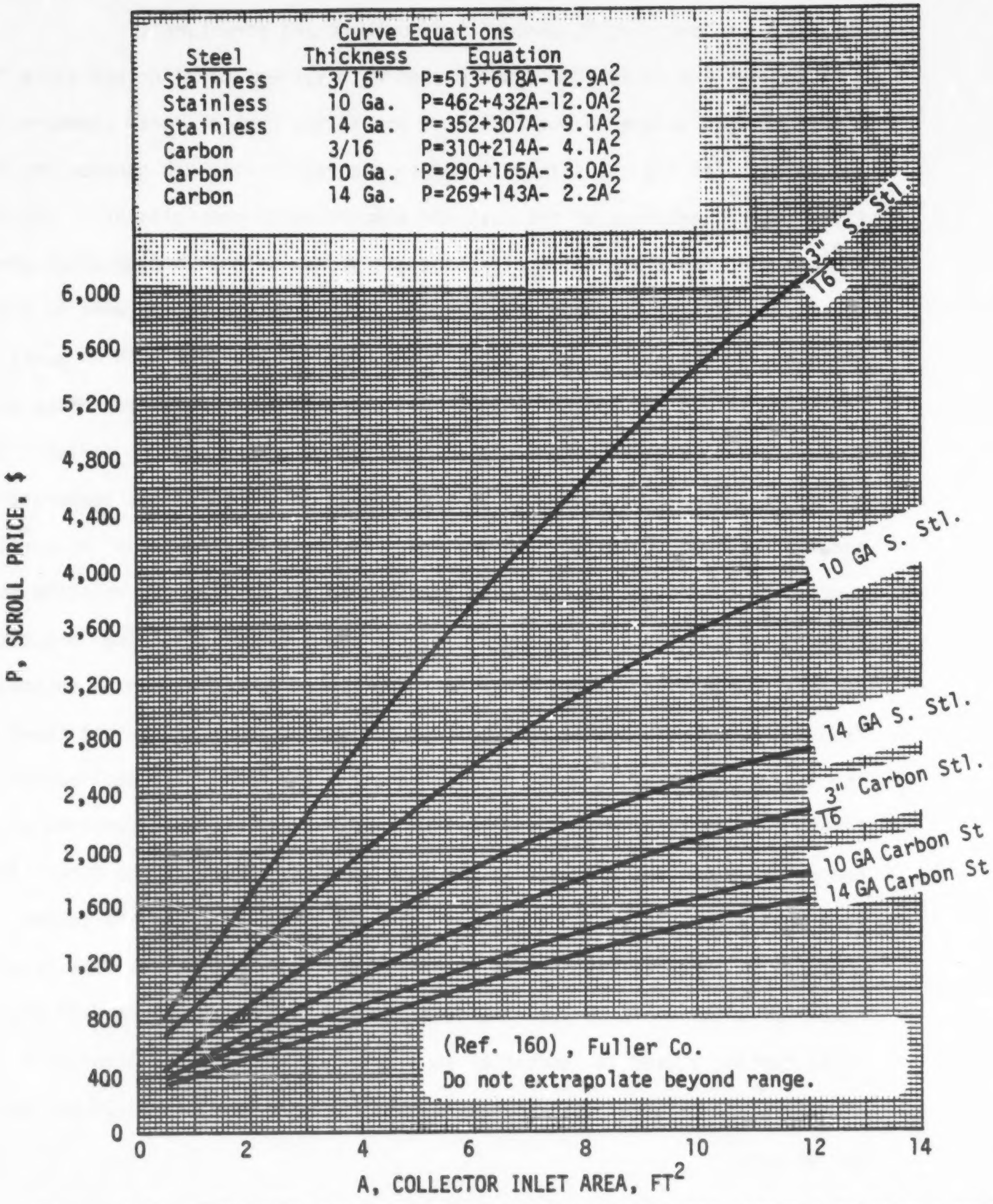


Figure 4-20 MECHANICAL COLLECTOR DUST HOPPER PRICES FOR CARBON & STAINLESS STEEL CONSTRUCTION VS. COLLECTOR INLET AREA



Curve Equations

Steel	Thickness	Equation
Stainless	3/16"	$P=513+618A-12.9A^2$
Stainless	10 Ga.	$P=462+432A-12.0A^2$
Stainless	14 Ga.	$P=352+307A-9.1A^2$
Carbon	3/16	$P=310+214A-4.1A^2$
Carbon	10 Ga.	$P=290+165A-3.0A^2$
Carbon	14 Ga.	$P=269+143A-2.2A^2$

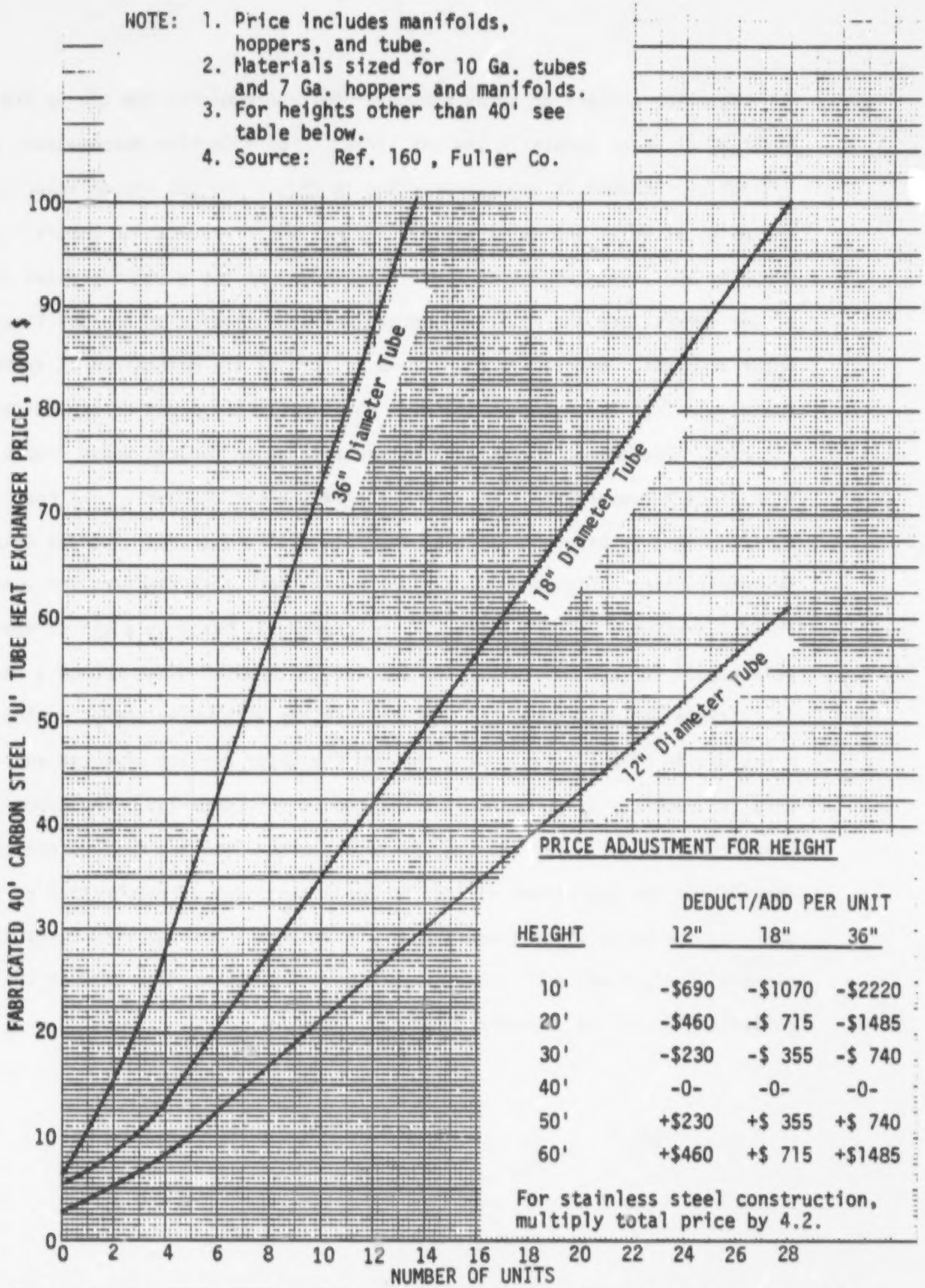
(Ref. 160), Fuller Co.
Do not extrapolate beyond range.

Figure 4-21 MECHANICAL COLLECTOR SCROLL OUTLET PRICES FOR CARBON & STAINLESS STEEL CONSTRUCTION VS. COLLECTOR INLET AREA

flow rate when the flow capacity exceeds that of a single unit. The price of these combination units can be estimated as the summation of the costs for each cyclone plus 20 percent for ductwork and structurals.

Coolers and spray chambers are used with systems handling hot gases to reduce the gas volume to the collector or, in the case of spray chambers, to add moisture to the gas stream to reduce the resistivity and enhance the electrical characteristics of the dust for electrostatic precipitators. Dry-type coolers used expressly for cooling the gas stream without adding water generally consist of radiant "U-tubes" of 30 to 60 feet in height and between 12 and 36 inches in diameter. These tubes are manifolded together both in parallel and in series to provide sufficient heat transfer surface to reduce the gas temperature to a value compatible with operation of the control device. The number of required "U-tubes" in series depends on the inlet gas temperature and the required outlet gas temperature. The number of "U-tubes" in parallel depends on the volume of gas being handled and the desired gas velocity per tube. A discussion of the design criteria and a method of sizing U-tubes coolers is contained in reference 88. The cost of a cooler can be estimated from the number of modular "U-tubes" of a given diameter and height based on the desired temperature drop and flow rate for the particular application. Figure 4-22 contains prices for U-tube radiant coolers as a function of the number of units, the diameter of the tube, and the height of the tube. The term "units" refers to the number of U-shaped tubes; e.g., if the cooler consists of three U-shaped tubes in series and four in parallel, the total number of units would be 12. The tube diameters shown in Figure 4-22 are those typically used in industrial applications, however, for other tube diameters and material thicknesses, a cost estimate based on $1.20 per pound may be used.

NOTE:
1. Price includes manifolds, hoppers, and tube.
2. Materials sized for 10 Ga. tubes and 7 Ga. hoppers and manifolds.
3. For heights other than 40' see table below.
4. Source: Ref. 160 , Fuller Co.



PRICE ADJUSTMENT FOR HEIGHT

HEIGHT	DEDUCT/ADD PER UNIT 12"	18"	36"
10'	-$690	-$1070	-$2220
20'	-$460	-$ 715	-$1485
30'	-$230	-$ 355	-$ 740
40'	-0-	-0-	-0-
50'	+$230	+$ 355	+$ 740
60'	+$460	+$ 715	+$1485

For stainless steel construction, multiply total price by 4.2.

Figure 4-22 FABRICATED 40 FT HIGH "U" TUBE HEAT EXCHANGER PRICES WITH HOPPERS AND MANIFOLDS

Wet-type coolers or spray chambers cool and humidify the gas by the addition of water sprays in the gas stream. For effective evaporation, a cylindrical chamber is usually provided to reduce the gas stream velocity at the point at which the water is injected and where evaporation occurs. The diameter and length of the chamber is dependent on the maximum droplet size of the sprays, and the relative temperature and velocity of the gas stream and water droplets. Generally, gas stream velocities are maintained at approximately 10 feet per second with inlet spray water pressures of approximately 100 psig. Increasing the water pressure results in reduced water droplet size, faster evaporation, and consequently, smaller chambers. The cost of spray coolers is based on the size and volume of the chamber and the materials of construction. Figure 4-23 contains prices for spray chambers for various inlet gas volumes. The diameter of the chamber is based on a gas stream velocity of 10 feet per second and the length is based on an L/D of 3 which is suitable for most spray cooling applications with water sprays at 100 psig. A discussion of the relationship between the water droplet diameter and the time for complete evaporation is contained in reference 155. The quantity of water required for spray cooling can be estimated from the desired change in enthalpy of the gas stream divided by the latent heat of evaporation of the water at the spray water temperature. This assumes that cooling takes place along a constant wet bulb temperature line. The volume flow rate at the cooler outlet can be determined by:

$$Q = \frac{1545\ T}{P} \quad \frac{W_{dg}}{(MW)_{dg}} + \frac{W_{wv}}{18}$$

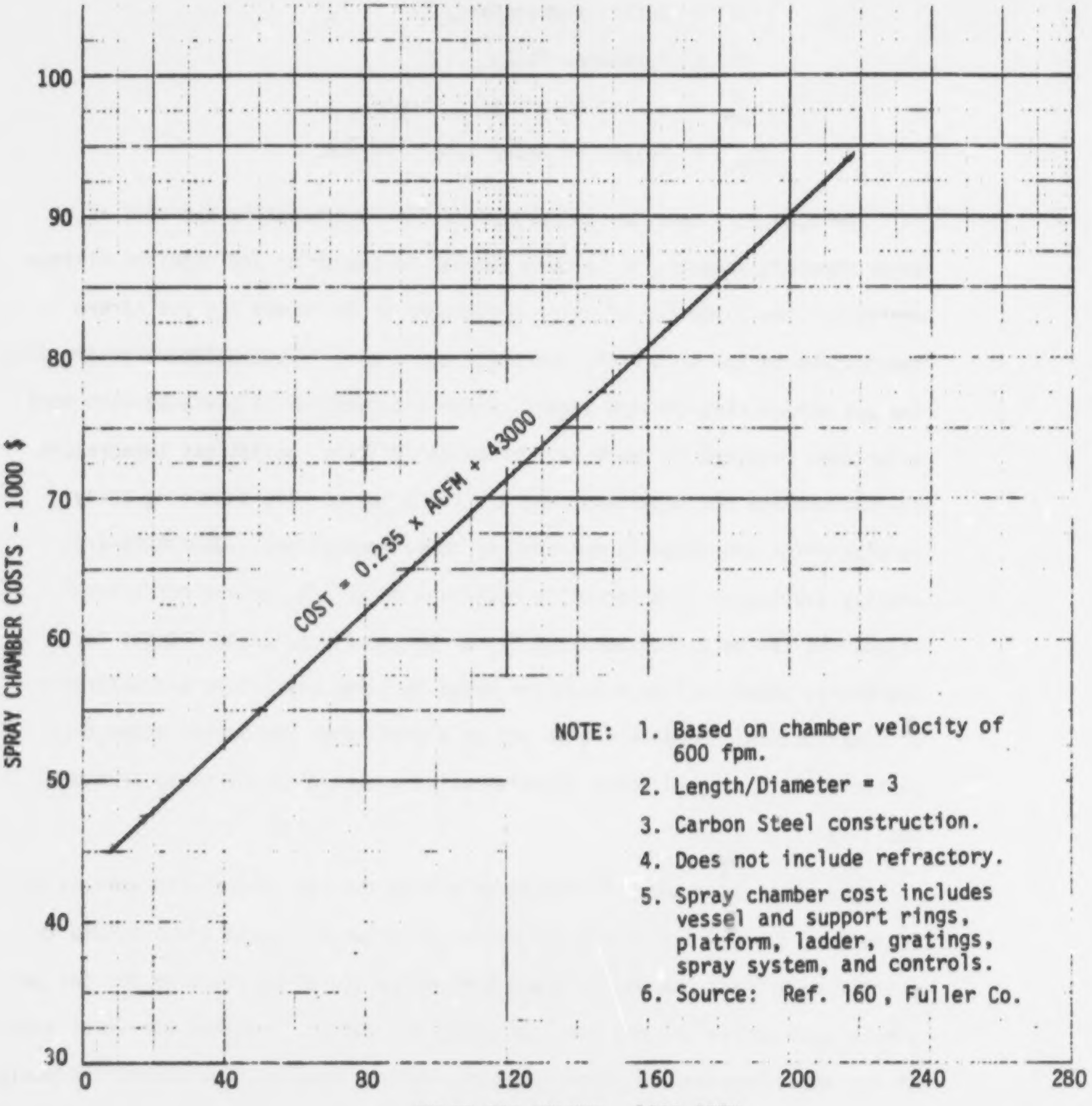


Figure 4-23 SPRAY CHAMBER COSTS VS. INLET GAS VOLUME

where: Q = Volume flow rate, cfm

T = Outlet temperature, °R

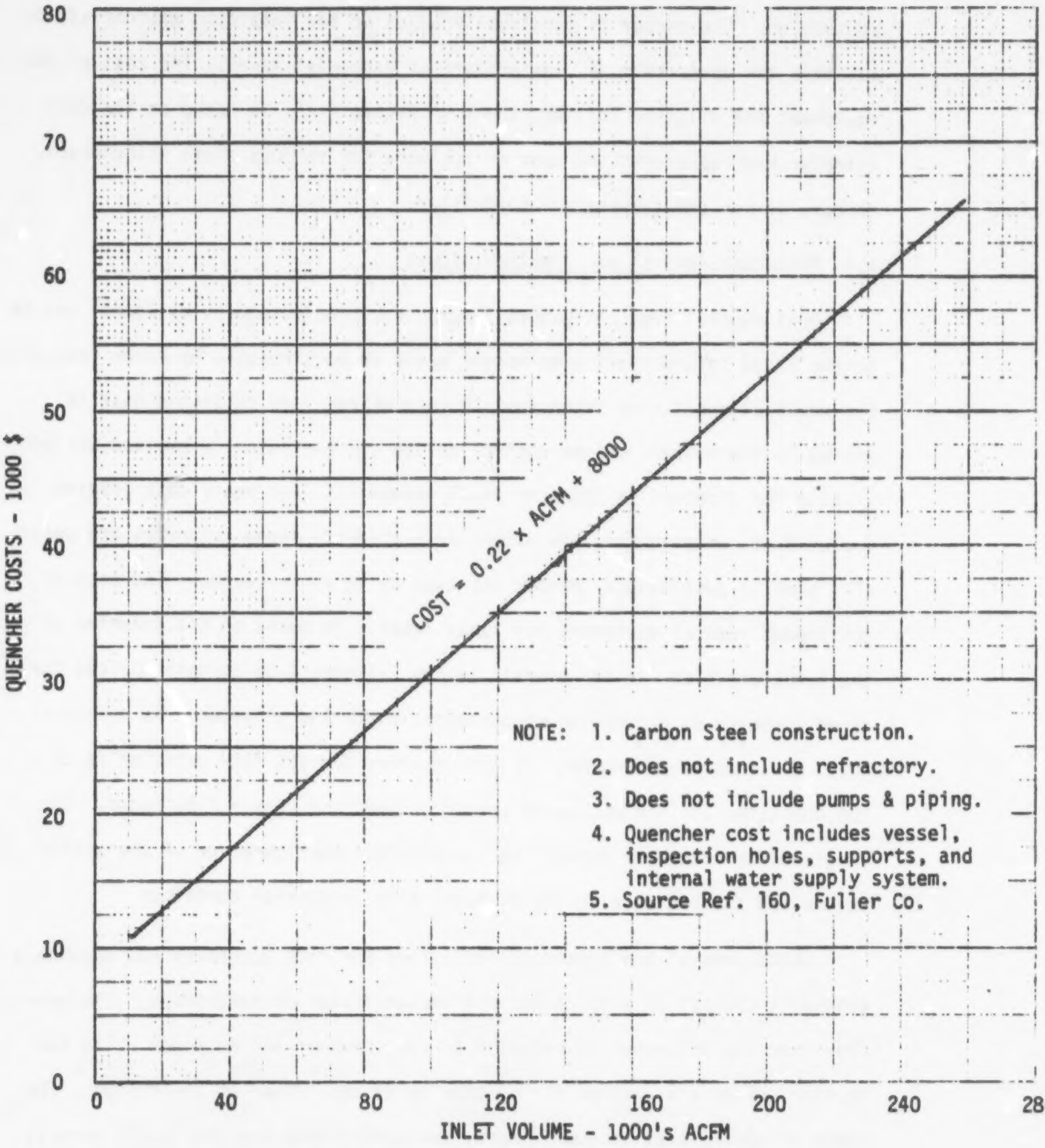
P = Pressure, lb/ft^2

W_{dg} = Weight of dry gas, lb/min

W_{wv} = Weight of water vapor, lb/min.

The quencher, used for hot processes, is fundamentally the same as a spray chamber; however, it is much simpler in operation and requires minimum controls. The objective of using a quencher is to reduce the gas stream temperature to the saturation temperature and this is accomplished by flooding the gas stream with cooling water. Since the quencher is operated with more water than required to reach saturation temperature, outlet gas temperature controllers are not necessary, nor are the banks of fine atomizing spray nozzles which are normally operated by these controllers. Quenchers are usually fabricated from corrosion resistant materials, or are refractory lined, and can be either horizontally or vertically oriented. Costs for quenchers, shown in Figure 4-24 are based on inlet gas volume and materials of construction. Quenchers also act as a precleaner for larger sized dust particles with the collected slurries being returned to the waste treatment facility.

The simplest method of cooling is mixing the gas stream with ambient air introduced through a dilution air port. Dilution air ports are provided to protect downstream components from "over-temperature" by diluting the hot gas stream with cooler ambient air. Dilution air cooling requires the least amount of equipment compared to other types of cooling; however, the downstream equipment such as the control device, fans, and ductwork are substantially increased in size (and cost) to compensate for the additional air. The components for dilution cooling generally consist of a duct tee, damper, and temperature



NOTE:
1. Carbon Steel construction.
2. Does not include refractory.
3. Does not include pumps & piping.
4. Quencher cost includes vessel, inspection holes, supports, and internal water supply system.
5. Source Ref. 160, Fuller Co.

Figure 4-24 QUENCHER COSTS VS. INLET GAS VOLUME

controller. The damper is continually adjusted for inspiring ambient air to maintain the downstream gas temperature at a pre-set level. The cost of the equipment for dilution cooling, shown in Figure 4-25, is based on the duct diameter and represents the cost of ductwork for various plate thicknesses, damper, sensor and temperature controller.

4.4 Pollutant Removal and Treatment (Dust)

Dust removal from collectors (baghouses, precipitators, cyclones) can be accomplished intermittently by manual means or continuously by screw conveyors. For applications having light dust concentrations, the collected dust is stored in the hoppers of the control device and periodically emptied through a valve for disposal by truck or local transport. For heavy dust loading (inlet dust concentrations in excess of 1 gr/dscf) screw conveyors are generally used to continuously remove the dust as it is collected. The cost of continuous removal equipment for heavy loading is based on the diameter of the screw conveyor and its overall length. Figure 4-26 contains prices for screw conveyor as a function of conveyor length and diameter. As a general rule, a 9-inch screw conveyor is satisfactory for gas flow rates of up to 100,000 acfm; 12-inch conveyors should be used for higher flow rates. The length of the conveyor depends on the physical configuration of the control device and the distance to the disposal site or storage container.

Waste removal and treatment facilities for both scrubbers and quenchers generally consist of a thickener and vacuum filter or centrifuge. The overflow from the thickener is recycled to the scrubber and quencher while the heavier solids are removed for dewatering by the filter or centrifuge. The costs of thickeners, vacuum filters, and centrifuges are completely covered in the following reports, also listed in Appendix C as source Nos. 119 and 128.

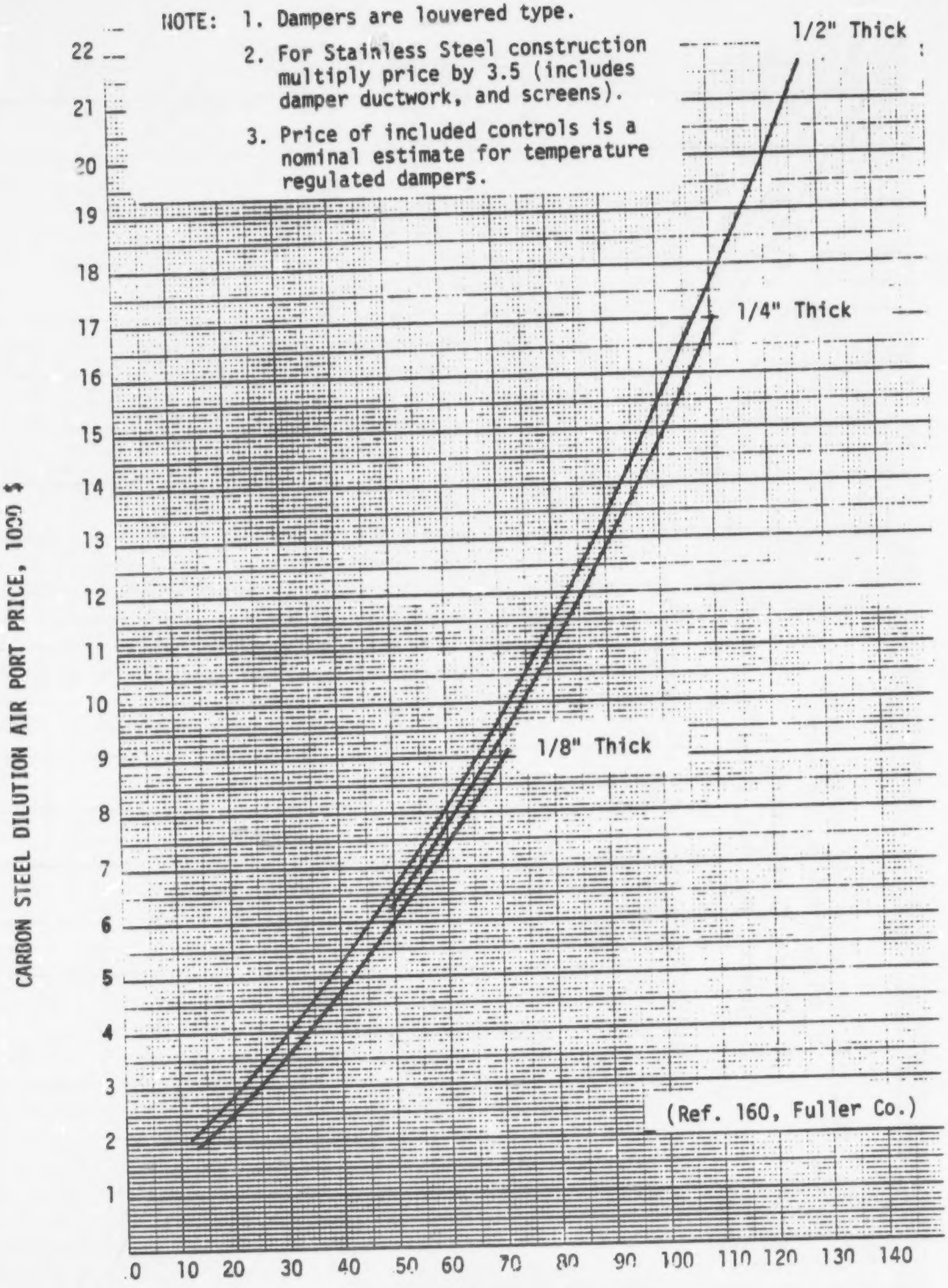
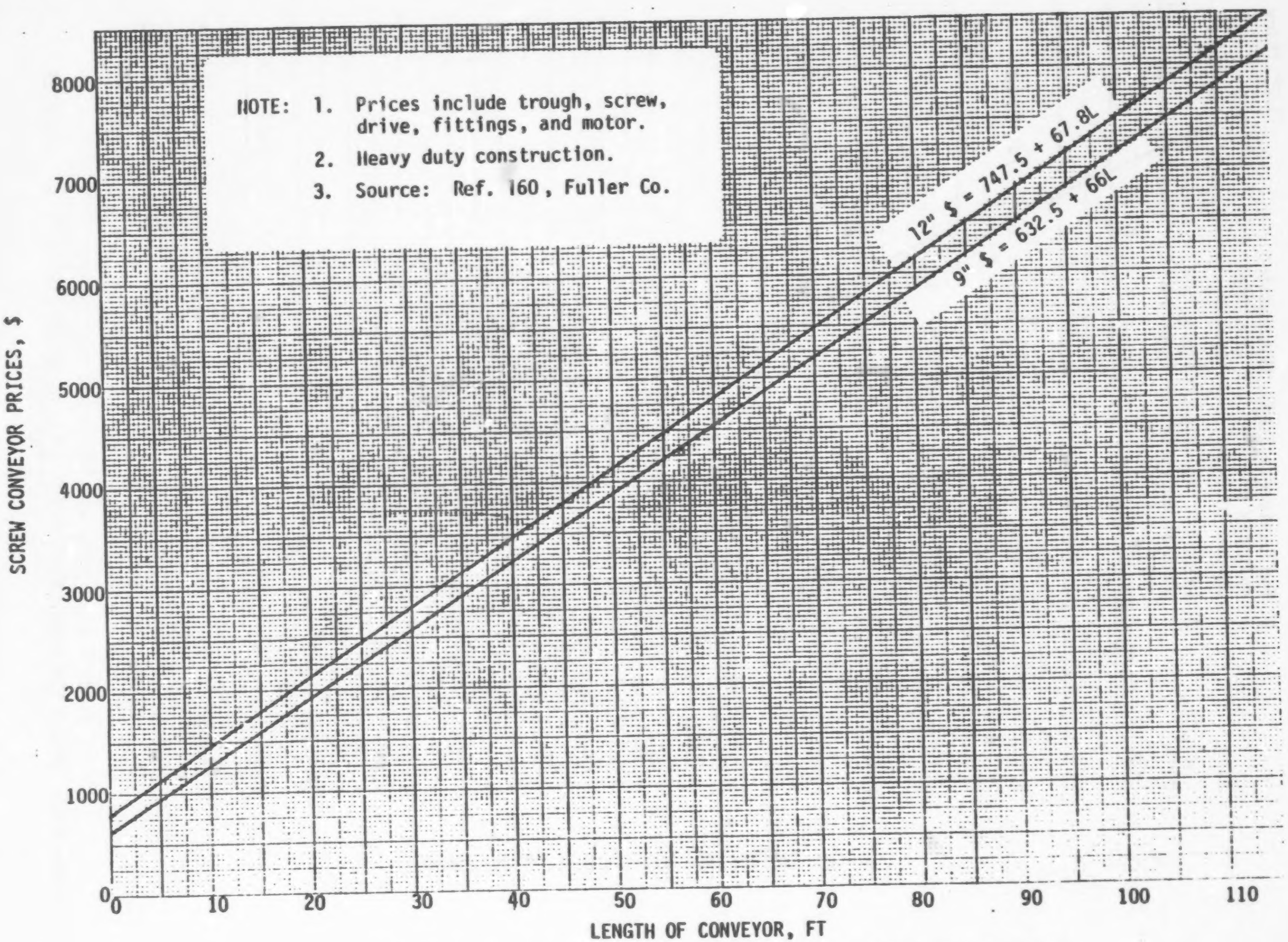


Figure 4-25 PRICES FOR FABRICATED CARBON STEEL DILUTION AIR PORTS VS. DIAMETER AND PLATE THICKNESS



NOTE:
1. Prices include trough, screw, drive, fittings, and motor.
2. Heavy duty construction.
3. Source: Ref. 160, Fuller Co.

Figure 4-26 PRICES FOR SCREW CONVEYORS VS. LENGTH AND DIAMETER

"Capital and Operating Costs of Pollution Control Equipment Modules", Vol. I and Vol. II, EPA-R5-73-023 a and b, July, 1973. NTIS PB 224-535 & PB 224-536.

"Estimating Costs and Manpower Requirements for Conventional Wastewater Treatment Facilities", EPA 17090 DAN 10/71. NTIS PB 211-132.

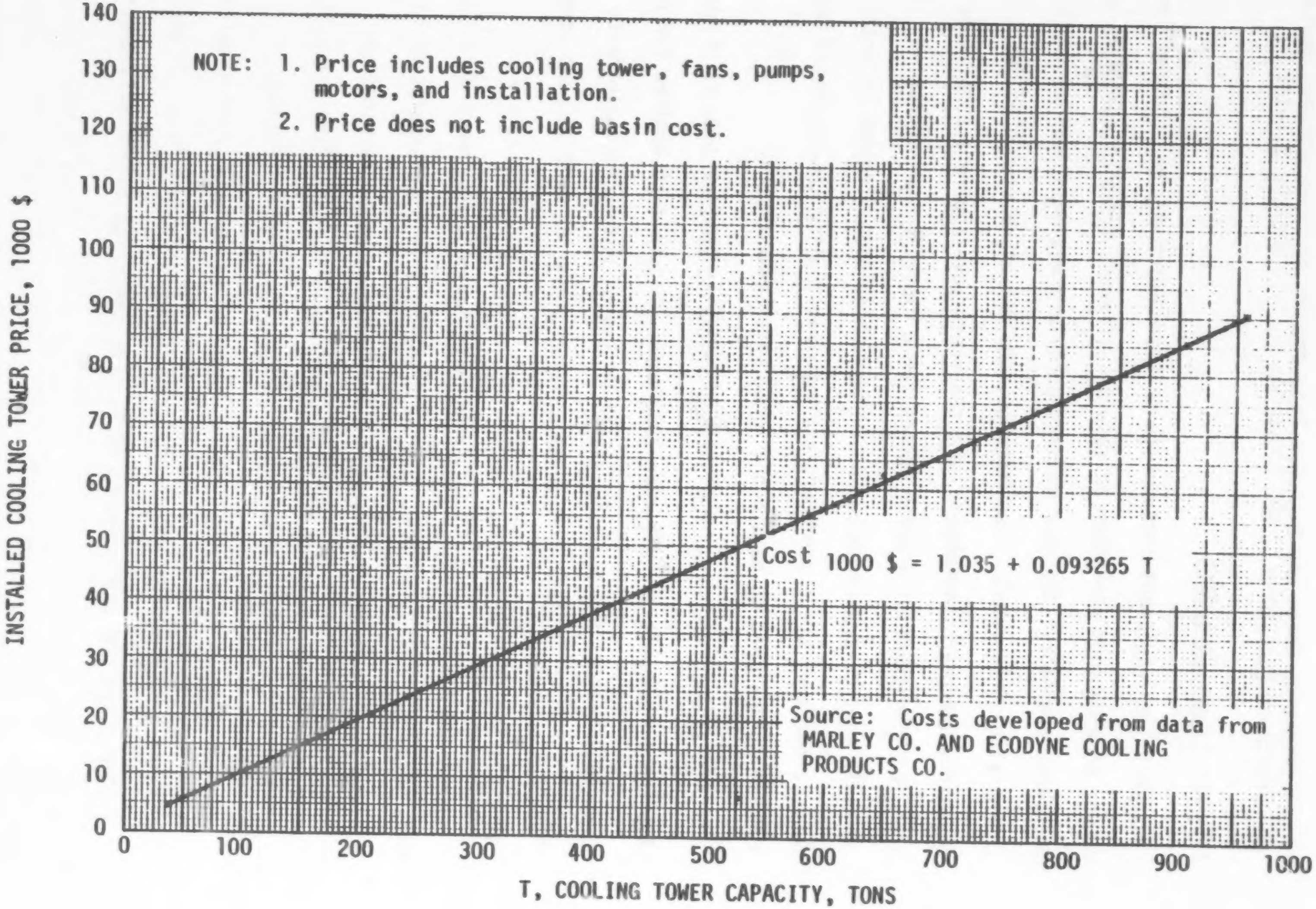
4.5 Ancilliary Equipment

Ancillary equipment includes those items which may be required for the proper simultaneous operation of several different types of auxiliary equipment and, therefore, the cost of this ancillary equipment can not be attributed to any single component. For instance, the use of water-cooled duct, spray chambers, quenchers, scrubbers, and absorbers may require a pump, some piping and a cooling tower as a water source for a closed-system operation. If a specific control system included a water-cooled hood, lengths of water-cooled duct, a quencher and a scrubber, the required cooling tower circuit would have to be designed to handle the total water requirements.

Two figures are given for pricing installed cooling towers. Figure 4-27 applies for capacities less than 1000 tons. Figure 4-28 applies for capacities over 1000 tons (1 ton = 12,000 Btu/hr of useful refrigeration effect, or 15,000 Btu/hr of heat rejected). The application of Figure 4-28 is more complicated and is explained below.

Figure 4-28 provides prices for installed cooling towers as a function of the range and the water flow rate at a wet bulb (W.B.) temperature of 82^{o}F and an approach of 10^{o}F. See Table 4.4 for definitions of terminology. If the W.B. is other than 82^{o}F, Table 4.5 provides factors for adjusting the price. If the approach is other than 10^{o}F, Table 4.6 provides similar factors.

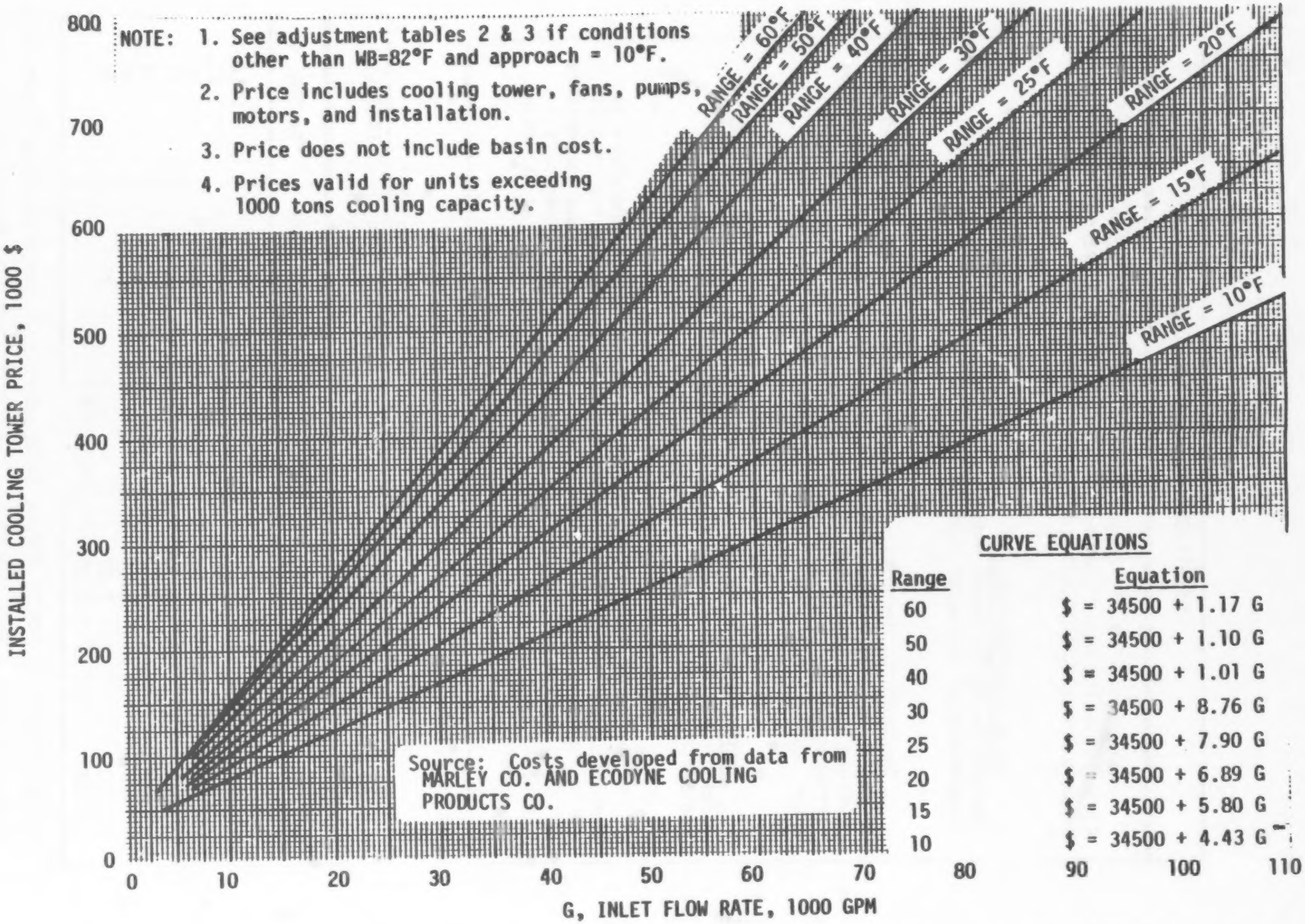
For example, suppose a cooling tower is to operate under conditions of 72^{o}F W.B. and a 20^{o}F approach (leaving water temperature = 92^{o}F). If the flow rate is 50,000 gpm and the range is 60^{o}F, then the price before adjustments is



NOTE: 1. Price includes cooling tower, fans, pumps, motors, and installation.
2. Price does not include basin cost.

Source: Costs developed from data from MARLEY CO. AND ECODYNE COOLING PRODUCTS CO.

Figure 4-27 PRICES FOR INSTALLED COOLING TOWERS FOR UNITS OF CAPACITY ≤ 1000 TONS



NOTE:
1. See adjustment tables 2 & 3 if conditions other than WB=82°F and approach = 10°F.
2. Price includes cooling tower, fans, pumps, motors, and installation.
3. Price does not include basin cost.
4. Prices valid for units exceeding 1000 tons cooling capacity.

Source: Costs developed from data from MARLEY CO. AND ECODYNE COOLING PRODUCTS CO.

CURVE EQUATIONS

Range	Equation
60	$ = 34500 + 1.17 G
50	$ = 34500 + 1.10 G
40	$ = 34500 + 1.01 G
30	$ = 34500 + 8.76 G
25	$ = 34500 + 7.90 G
20	$ = 34500 + 6.89 G
15	$ = 34500 + 5.80 G
10	$ = 34500 + 4.43 G

Figure 4-28 PRICES FOR INSTALLED COOLING TOWER BASED ON WET-BULT TEMPERATURE = 82°F AND APPROACH = 10°F

Table 4.4

DEFINITIONS FOR COOLING TOWER

Approach: The difference between the average temperature of the circulating water leaving the device, and the average wet-bulb temperature of the entering air.

Range (cooling range): The difference between the average temperature of the water entering the device, and the average temperature of the water leaving it.

Temperature, dewpoint: The temperature at which the condensation of water vapor in a space begins for a given state of humidity and pressure as the temperature of the vapor is reduced. The temperature corresponding to saturation (100 percent relative humidity) for a given absolute humidity at constant pressure.

Temperature, dry-bulb: The temperature of a gas or mixture of gases indicated by an accurate thermometer after correction for radiation.

Temperature, wet-bulb: Thermodynamic wet-bulb temperature is temperature at which liquid or solid water, by evaporating into air, can bring the air to saturation adiabatically at the same temperature. Wet-bulb temperature (without qualification) is the temperature indicated by a wet-bulb psychrometer constructed and used according to specifications.

Table 4.5

PRICE ADJUSTMENT FACTORS*
FOR WET-BULB TEMPERATURES

WET-BULB, °F	FACTOR, F_2
68	1.54
70	1.46
72	1.38
74	1.30
76	1.22
78	1.15
80	1.07
82	1.00

Table 4.6

PRICE ADJUSTMENT FACTORS*
FOR APPROACH ΔT

APPROACH, Δ°F	FACTOR, F_1
6	1.60
8	1.20
10	1.00
12	.85
16	.65
20	.50
24	.40

* New Price = (P-34500) $F_1 F_2$ + 34500 where P is the price from Figure 4-28.

** Data developed from MARLEY CO. and ECODYNE COOLING PRODUCTS CO.

$620,000. The adjustment factor for 72°F W.B. is 1.38 and the factor for a 20°F approach is 0.5. The installed cooling tower price is thus:

$$(620,000 - 34,500)\ (0.5)\ (1.38) + 34,500 = \sim \$438,500$$

The fan motor horsepower is estimated as follows:

$$HP = \frac{P}{1500}, \text{ where P is the price of the tower.}$$

The pump motor horsepower is estimated as follows:

$$HP - gpm \times 0.12.$$

The basin area is estimated as follows:

$$\text{Basin Area} = \frac{P}{150}\ ft^2.$$

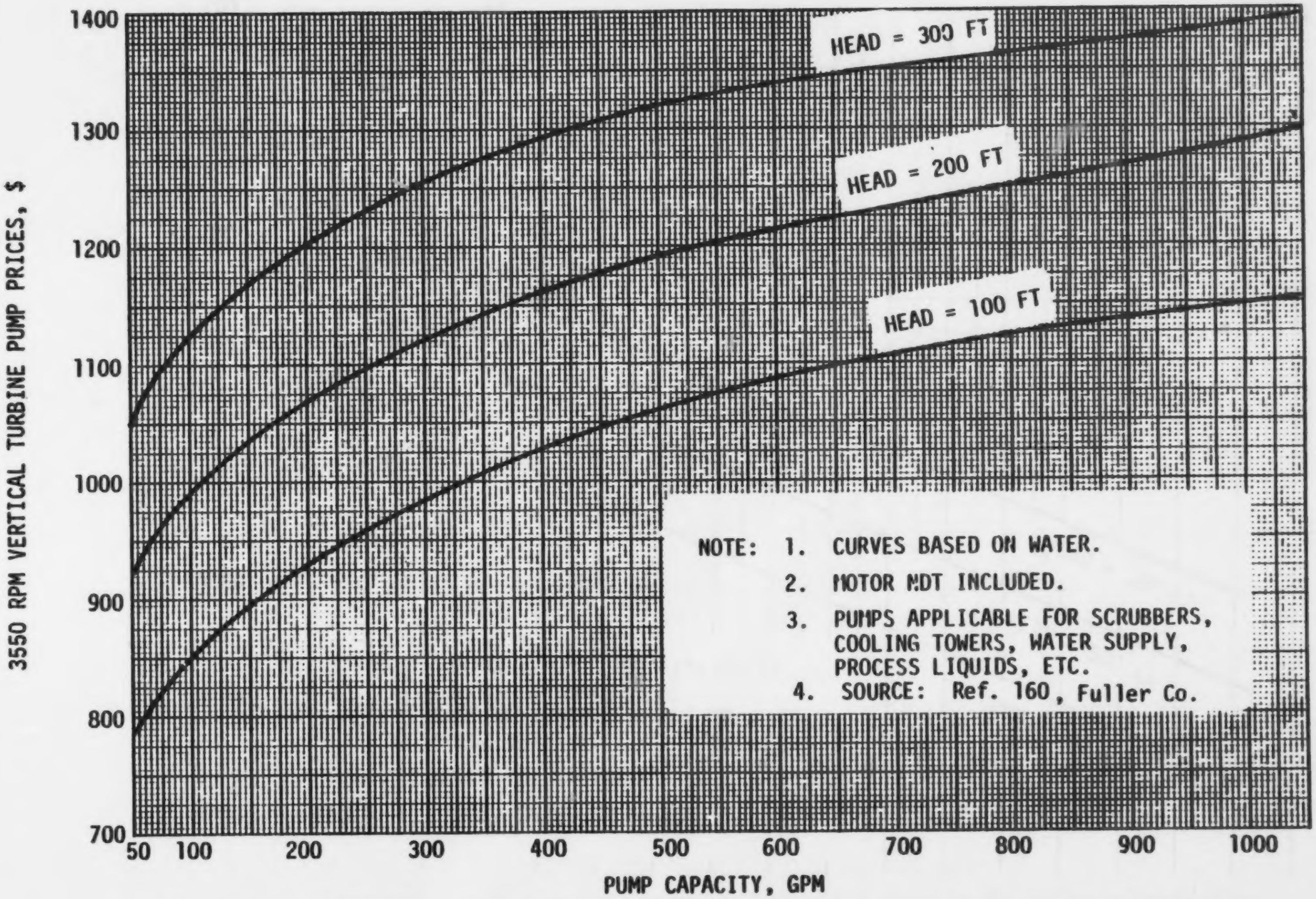
Since the approach in this example (the difference between the temperature of the outlet water and the wet-bulb temperature of the inlet air) is greater than 10°F, the difference in enthalpy between the air and the water is greater and consequently a smaller and less costly cooling tower would be required for the same heat transfer capacity and ratio of gas-to-liquid flow rate. On the other hand, because the wet-bulb temperature is lower than 82°F (72°F, in this example), its absolute humidity is also lower. (In other words, one pound of air with an 82^{O}F wet bulb temperature is capable of carrying more water than a pound of air with a 72^{O}F wet bulb temperature). As a result, to cool the same amount of water by evaporation, more air at 72^{O}F W.B. would be required than at 82^{O}F W.B. This, in turn, would require a relatively larger cooling tower. Hence, the cost adjustment factor taken from Table 4.5 (1.38 in this example) would be greater than 1.0.

Basins costs have not been provided since they vary so widely with the individual application. The basin may be used in conjunction with other processes, which involves a proration of costs, and the basin may be constructed in many types of soil and terrain, which can dramatically alter the first cost. Basin costs should be estimated on an application basis through a basin contractor. As a rough estimate, the installed cost of the basin can be considered to be approximately $70 per sq. ft. for the size of cooling towers shown in Figures 4-27 and 4-28.

Figures 4-29, 4-30 and 4-31 contain prices for 3550 RPM, 1750 RPM, and 1170 RPM cast iron, bronze fitted, vertical turbine wet sump pumps. These pumps can be used for scrubbers, cooling towers, water cooled duct, water supply, and similar applications. Prices are a function of pump head in feet and pump capacity in gpm. The selection of the rpm of these pumps should be based on the design flow rate range of the application as shown below.

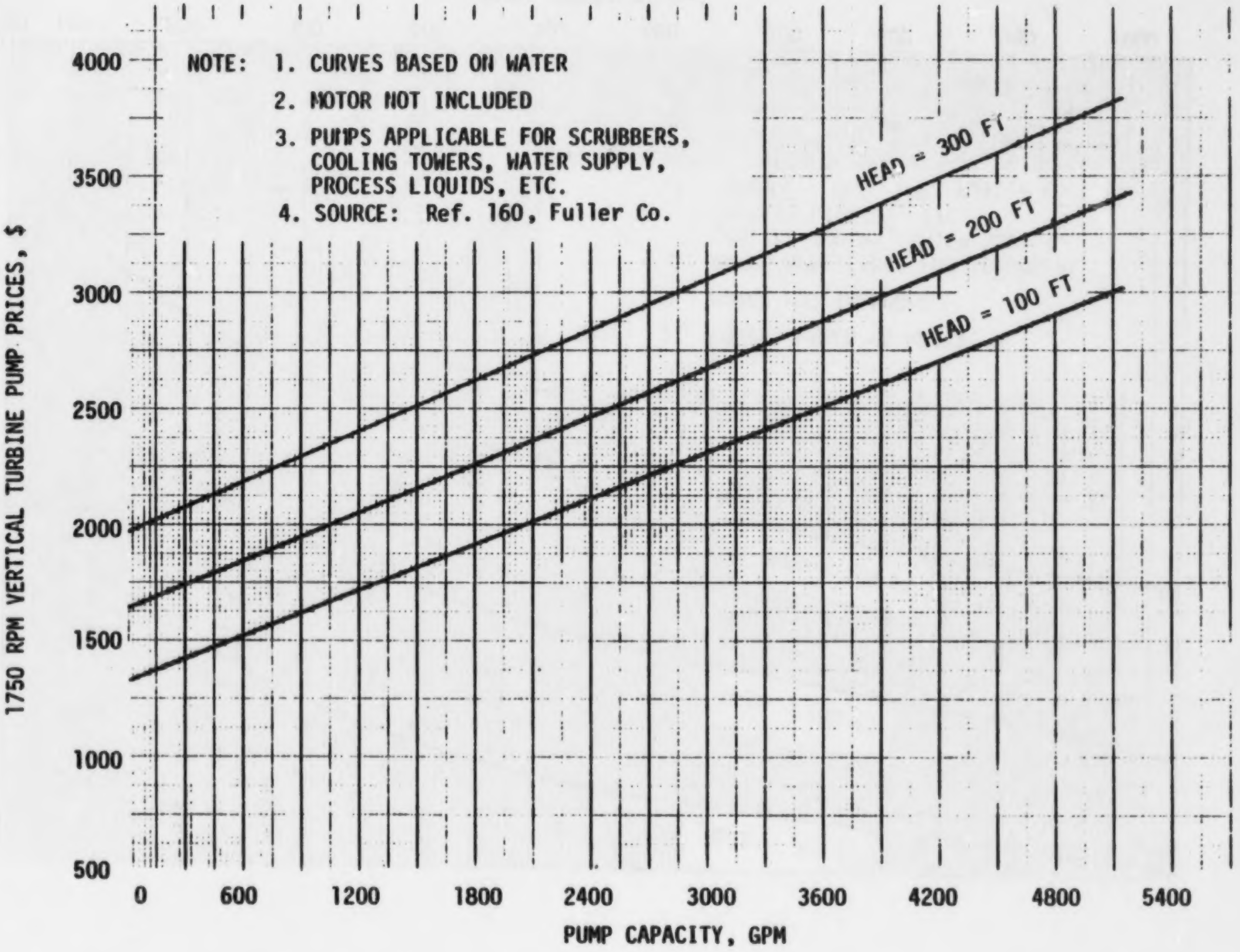
FLOW RATE (gpm)	PUMP (rpm)
0-1,000	3,550
500-5,000	1,750
2,000-10,000	1,170

Generally, the capital cost of the pump/motor combination varies inversely with the rpm; however, maintenance costs can be expected to higher as rpm increases. Figure 4-32 provides a means of estimating pump motor horsepower for a given pump head and capacity. These curves represent the nominal motor sizes used for the indicated pump heads and capacities. If the characteristics of a specific pump (i.e., pump curve and rated efficiency) are known, the equation in Section 3 may be used to determine the motor size. In this case, the selected motor must be a standard size. Motor prices may then be estimated using Figure 4-34 provided in Section 4.6.



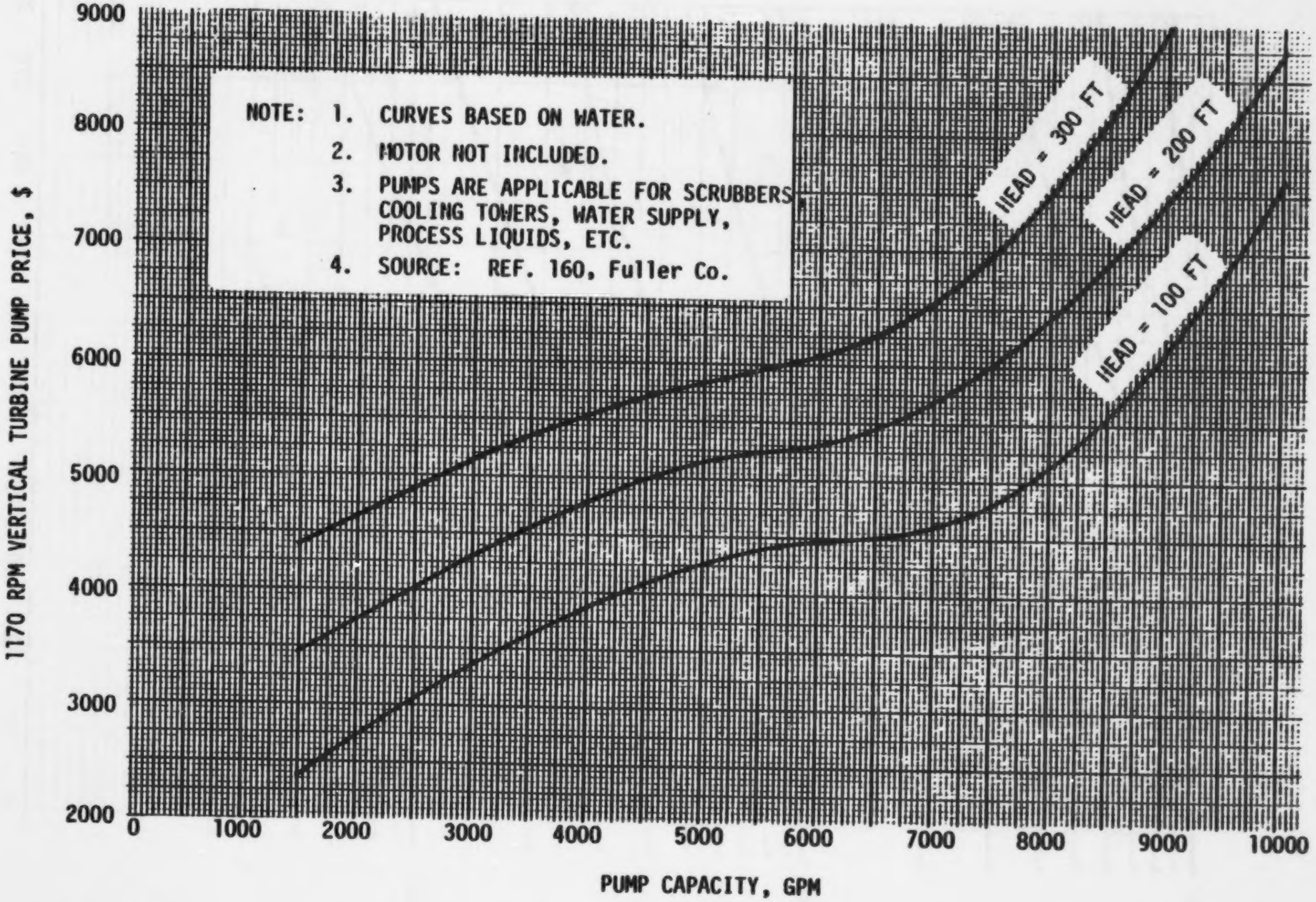
NOTE: 1. CURVES BASED ON WATER.
2. MOTOR NOT INCLUDED.
3. PUMPS APPLICABLE FOR SCRUBBERS, COOLING TOWERS, WATER SUPPLY, PROCESS LIQUIDS, ETC.
4. SOURCE: Ref. 160, Fuller Co.

Figure 4-29 CAST IRON, BRONZE FITTED, VERTICAL TURBINE WET SUMP PUMP PRICES FOR 3550 RPM



NOTE: 1. CURVES BASED ON WATER
2. MOTOR NOT INCLUDED
3. PUMPS APPLICABLE FOR SCRUBBERS, COOLING TOWERS, WATER SUPPLY, PROCESS LIQUIDS, ETC.
4. SOURCE: Ref. 160, Fuller Co.

Figure 4-30 CAST IRON, BRONZE FITTED, VERTICAL TURBINE WET SUMP PUMP PRICES FOR 1750 RPM



NOTE:
1. CURVES BASED ON WATER.
2. MOTOR NOT INCLUDED.
3. PUMPS ARE APPLICABLE FOR SCRUBBERS, COOLING TOWERS, WATER SUPPLY, PROCESS LIQUIDS, ETC.
4. SOURCE: REF. 160, Fuller Co.

Figure 4-31 CAST IRON, BRONZE FITTED, VERTICAL TURBINE WET SUMP PUMP PRICES FOR 1170 RPM

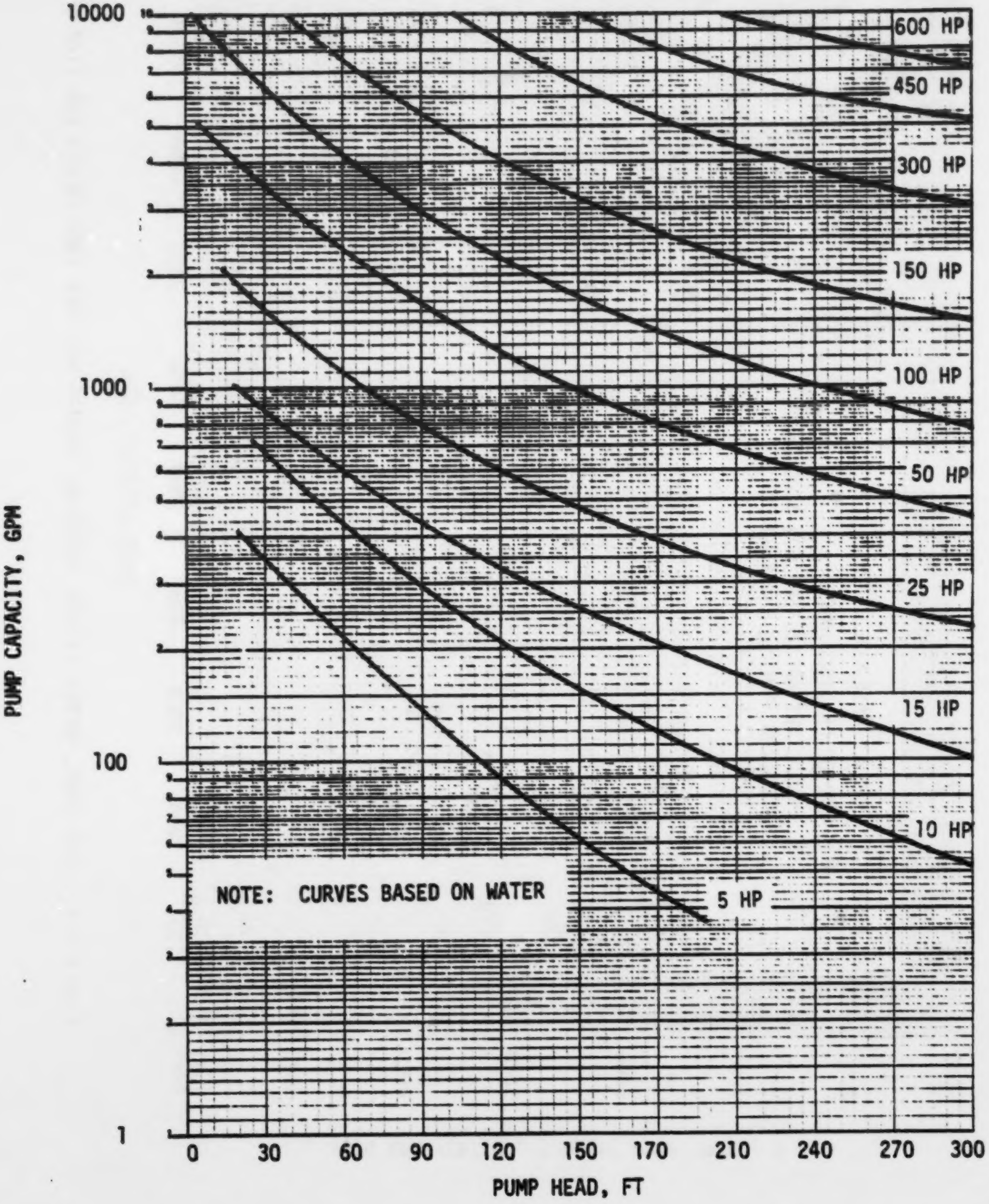


Figure 4-32 PUMP MOTOR HP VS. CAPACITY AND HEAD FOR VERTICAL TURBINE PUMPS

4.6 Fans

Centrifugal fans, having either backward curved or radial tip blades, are used almost exclusively to transport the dust-laden gases through the system. The backward curved fan provides the highest efficiency, but because of its inherent design, must be used downstream of the control device where the gas stream is relatively dust-free. These fans are categorized into Classes I through IV according to maximum impeller speeds and pressures. The cost of the fan is based on its construction, class, volume, and pressure delivered at standard conditions. The radial tip fan, sometimes referred to as the industrial fan, operates at a lower efficiency, but is capable of handling dusty gas streams and can be used upstream of the control device. The impeller of this fan consists of flat radial paddles which can be modified to include wear plates for abrasive dust applications. These fans can also be operated at high temperatures. The cost of this type of fan is based on material of construction, total volume, and pressure delivered at standard conditions.

Radial tip fans are used almost exclusively in venturi scrubber control systems because of their ability to operate at high pressures and temperatures with abrasive gas streams. With scrubber systems, a certain amount of carryover of dust-laden water droplets can be expected which would be destructive to other types of fans operating at the impeller tip velocities necessary for 20-80 inches W.G. pressures. The radial tip fan can also be protected with wear plates and water sprays (for cleaning blades) for dirty or highly abrasive gas streams. The cost of radial blade fans is a function of the actual volume in cfm and the total pressure delivered based on incremental pressure ranges of 20, 40 and 60 inches W.G. Construction can be either carbon steel for general purposes or stainless steel for corrosive gases. Special linings are also available for unique conditions.

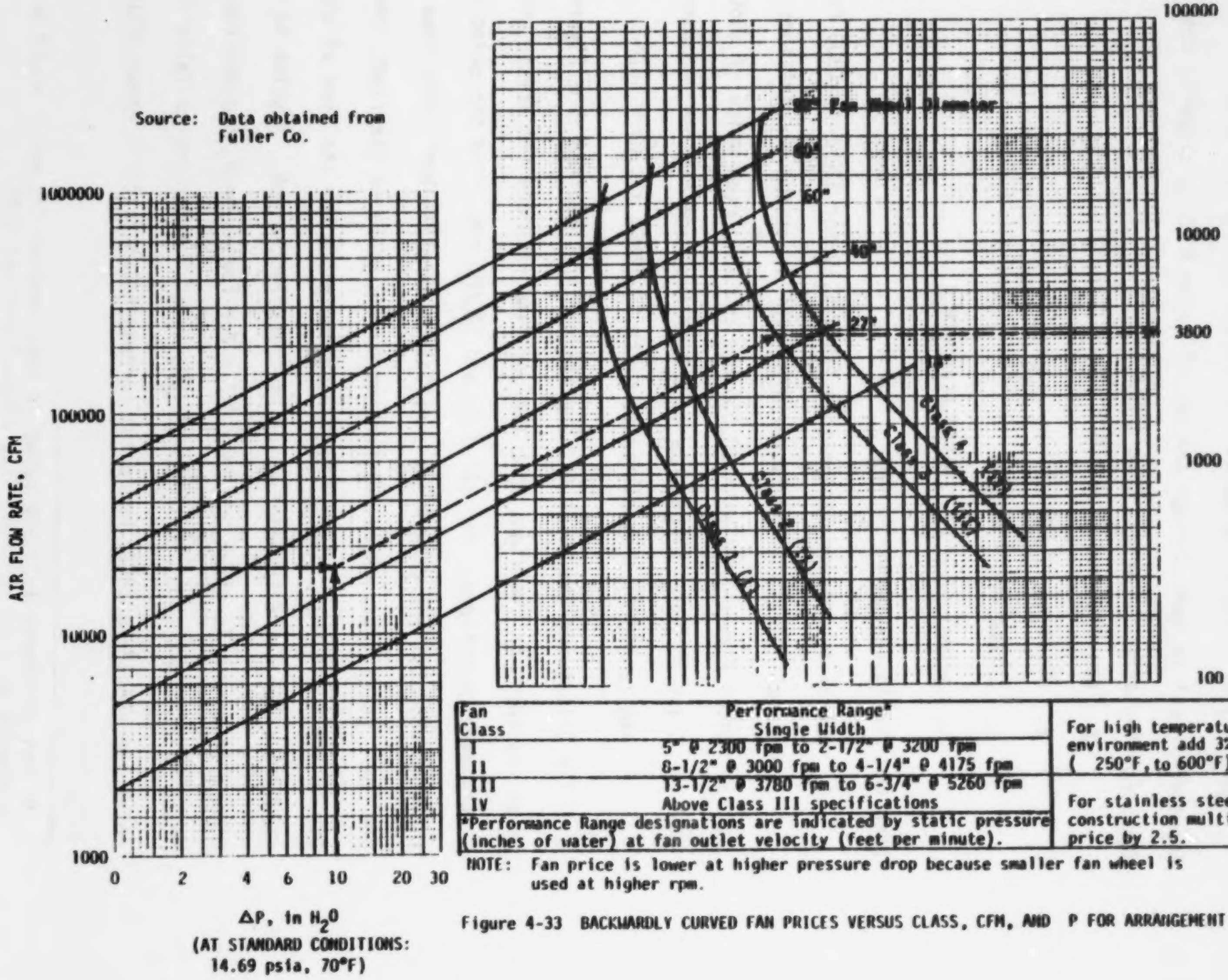
The cost of the motor and motor starter for centrifugal fans is related to the fan speed, total system pressure, gas volume flow rate, and selected motor housing. Fan speeds are chosen from a continuum, with aid of the fan laws, to provide a desired head at a prescribed flow. Motor speeds are chosen from a set of perhaps only five discrete choices (Table 4.7). Since belts and pulleys are routinely used, fan speed and motor speed should be selected as close to each other as possible. The motor housings should be chosen for the particular environment in which it will be operating. Drip-proof motors should be used in areas which are weather protected and relatively clean. Totally enclosed motors should be used in dusty areas or areas exposed to weather and severe splashing. Explosion-proof motors must be used in hazardous atmospheres where explosive fumes are present.

Backwardly curved fans are priced as a function of the actual air flow rate, pressure drop at standard conditions, and class, as given in Figure 4-33. Standard conditions are defined as:

pressure:	14.69 psia (sea level)
temperature:	70°F
gas density:	0.075 lb/ft^3

In many cases, fans are operated at different temperatures and pressures (altitudes) and, therefore, a correction factor must be applied to equate the actual operating conditions to a standard condition. This correction factor may be either a volume adjustment or a pressure adjustment. In the following figures, a pressure correction factor is used, therefore, the actual pressure of the fan at operating conditions must be adjusted to standard conditions to determine the size and cost of the fan. If, for example, a Class III fan is

Source: Data obtained from Fuller Co.



Fan Class	Performance Range* Single Width	
I	5" @ 2300 fpm to 2-1/2" @ 3200 fpm	For high temperature environment add 3% (250°F, to 600°F)
II	8-1/2" @ 3000 fpm to 4-1/4" @ 4175 fpm	
III	13-1/2" @ 3780 fpm to 6-3/4" @ 5260 fpm	For stainless steel construction multiply price by 2.5.
IV	Above Class III specifications	

*Performance Range designations are indicated by static pressure (inches of water) at fan outlet velocity (feet per minute).

NOTE: Fan price is lower at higher pressure drop because smaller fan wheel is used at higher rpm.

Figure 4-33 BACKWARDLY CURVED FAN PRICES VERSUS CLASS, CFM, AND P FOR ARRANGEMENT NO. 1

to operate at sea level with gas temperature of 70°F and is to handle a gas volume of 20,000 CFM at 10" water, the price would be $3800.

However, if a fan operates at a different pressure or temperature, an adjustment must be made through the use of Table 4.10 to properly cost the fan. For instance, if actual conditions are:

a. gas temperature = 300°F
b. altitude = 1000 ft.
c. actual cfm = 50,000
d. actual ΔP = 10" static pressure

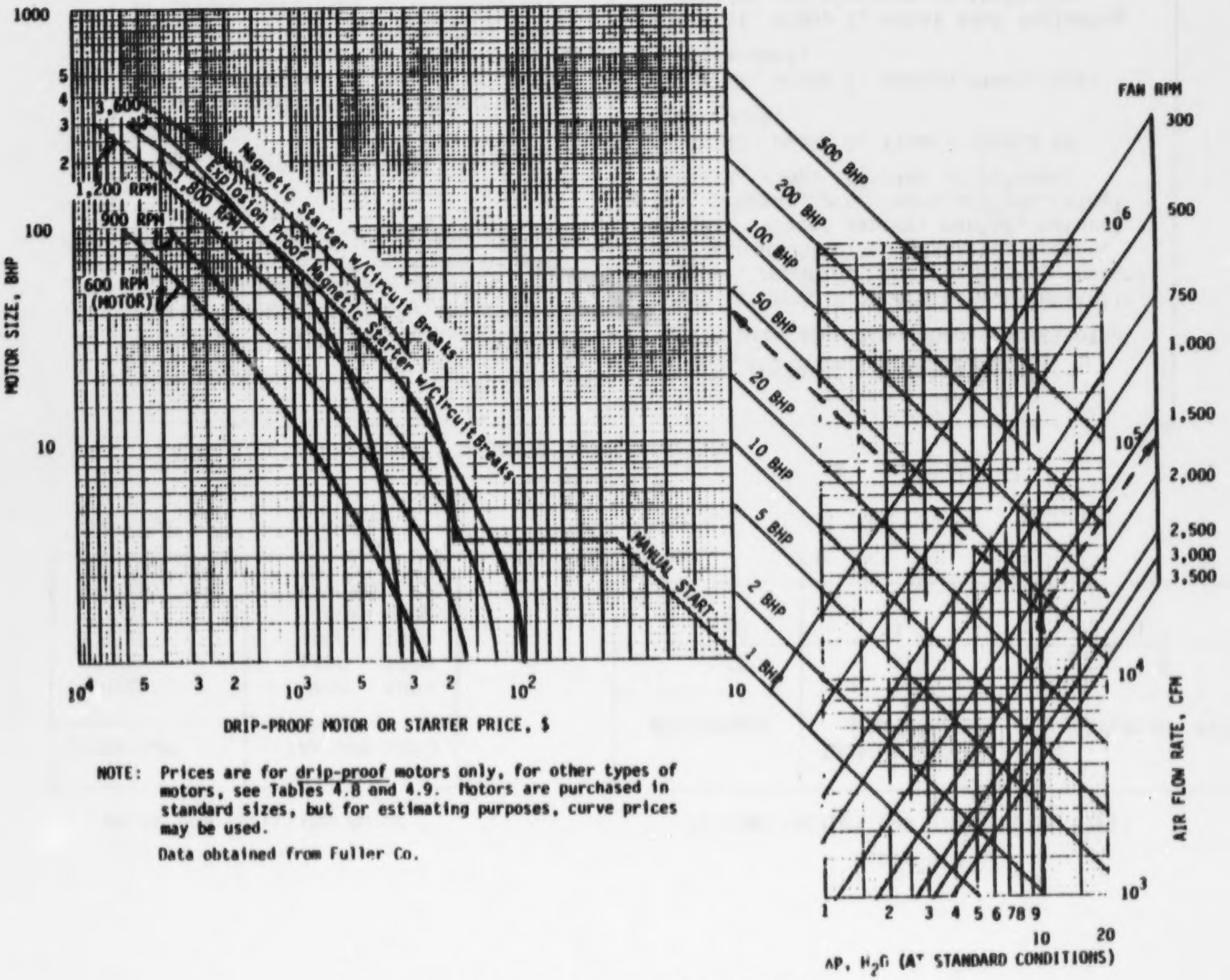
then the fan is priced as follows:

1. obtain fan sizing factor from Table 4.10 for 300°F at 1000 ft = .672
2. actual 10" static pressure/.672 = 15" at standard conditions
3. enter Figure 4-33 with 50,000 cfm and 15", read price of $8500 for Class IV fan. Since this is a high heat application, (temperatures of 250 to 600°F), the estimated price is $8500 x 1.03 = $8760.

The prices for the motor and the starter are obtained from Figure 4-34. Enter the chart on the right with the gas flow rate and the static pressure at standard conditions. For 10" S.P. and 20,000 cfm, find the point with those coordinates and draw lines parallel to the "FAN RPM" guidelines and the "BHP" guidelines. Read the fan rpm on the scale to the right, read the bhp on the scale to the left. Then read the price for the type of starter needed and for the drip-proof motor at the selected rpm. A guide to determining motor rpm is given in Table 4.7. For the example, the fan rpm is found to be about 1600 and the motor bhp is 44. According to Table 4.7, the motor rpm should be 1800, hence the corresponding price is about $700.*

---

* Prices in Figure 4-33 are based on bhp, however the motor would be purchased as a 50 hp motor (the closest nominal size).



NOTE: Prices are for drip-proof motors only, for other types of motors, see Tables 4.8 and 4.9. Motors are purchased in standard sizes, but for estimating purposes, curve prices may be used.

Data obtained from Fuller Co.

Figure 4-34 BHP, FAN RPM AND MOTOR AND STARTER PRICES VS. ΔP AND CFM

Table 4.7

MOTOR RPM SELECTION GUIDE

MOTOR RPM	FAN RPM RANGE
3600	2400 - 4000
1800	1400 - 2400
1200	1000 - 1400
900	700 - 1000
600	< 700

Table 4.8

PRICING FACTORS FOR OTHER MOTOR TYPES

HORSEPOWER	TOTALLY ENCLOSED FAN COOLED	EXPLOSION PROOF
≤ 20	1.3	1.6
> 20	1.5	1.7

Table 4.9

MOTOR TYPE SELECTION

Drip-proof: In non-hazardous, reasonably clean surroundings free of any abrasive or conducting dust and chemical fumes. Moderate amounts of moisture or dust and falling particles or liquids can be tolerated. Totally Enclosed Non-Ventilated or Fan Cooled: In non-hazardous atmospheres containing abrasive or conducting dusts, high concentrations of chemical or oil vapors and/or where hosing down or severe splashing is encountered.	Totally Enclosed Explosion Proof: Use in hazardous atmospheres containing: Class I, Group D, acetone, acrylonitrile, alcohol, ammonia, benzine, benzol, butane ethylene dichloride, gasoline, hexane, lacquer solvent vapors, naptha, natural gas, propane, propylene, styrene, vinyl acetate, vinyl chloride or xylenes; Class II, Group G, flour, starch or grain dust; Class II, Group F, carbon black, coal or coke dust; Class II, Group E, metal dust including magnesium and aluminum or their commercial alloys.

Data obtained from Fuller Co.

Table 4.10 FAN SIZING FACTORS: AIR DENSITY RATIOS

Unity Basis = Standard Air Density of .075 $\mathrm{lb/ft^3}$

At sea level (29.92 in. Hg barometric pressure) this is equivalent to dry air at 70°F.

Air Temp. °F	Altitude in Feet Above Sea Level												
	0	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000	15000	20000
	Barometric Pressure in Inches of Mercury												
	29.92	28.86	27.82	26.82	25.84	24.90	23.98	23.09	22.22	21.39	20.58	16.89	13.75
70	1.000	.964	.930	.896	.864	.832	.801	.772	.743	.714	.688	.564	.460
100	.946	.912	.880	.848	.818	.787	.758	.730	.703	.676	.651	.534	.435
150	.869	.838	.808	.770	.751	.723	.696	.671	.646	.620	.598	.490	.400
200	.803	.774	.747	.720	.694	.668	.643	.620	.596	.573	.552	.453	.369
250	.747	.720	.694	.669	.645	.622	.598	.576	.555	.533	.514	.421	.344
300	.697	.672	.648	.624	.604	.580	.558	.538	.518	.498	.480	.393	.321
350	.654	.631	.608	.586	.565	.544	.524	.505	.486	.467	.450	.369	.301
400	.616	.594	.573	.552	.532	.513	.493	.476	.458	.440	.424	.347	.283
450	.582	.561	.542	.522	.503	.484	.466	.449	.433	.416	.401	.328	.268
500	.552	.532	.513	.495	.477	.459	.442	.426	.410	.394	.380	.311	.254
550	.525	.506	.488	.470	.454	.437	.421	.405	.390	.375	.361	.296	.242
600	.500	.482	.465	.448	.432	.416	.400	.386	.372	.352	.344	.282	.230
650	.477	.460	.444	.427	.412	.397	.382	.368	.354	.341	.328	.269	.219
700	.457	.441	.425	.410	.395	.380	.366	.353	.340	.326	.315	.258	.210

SOURCE: AMCA STANDARD #402-66
AIR MOVING AND CONDITIONING ASSOCIATION, INC.
205 West Touhy Avenue
Park Ridge, Illinois 60068

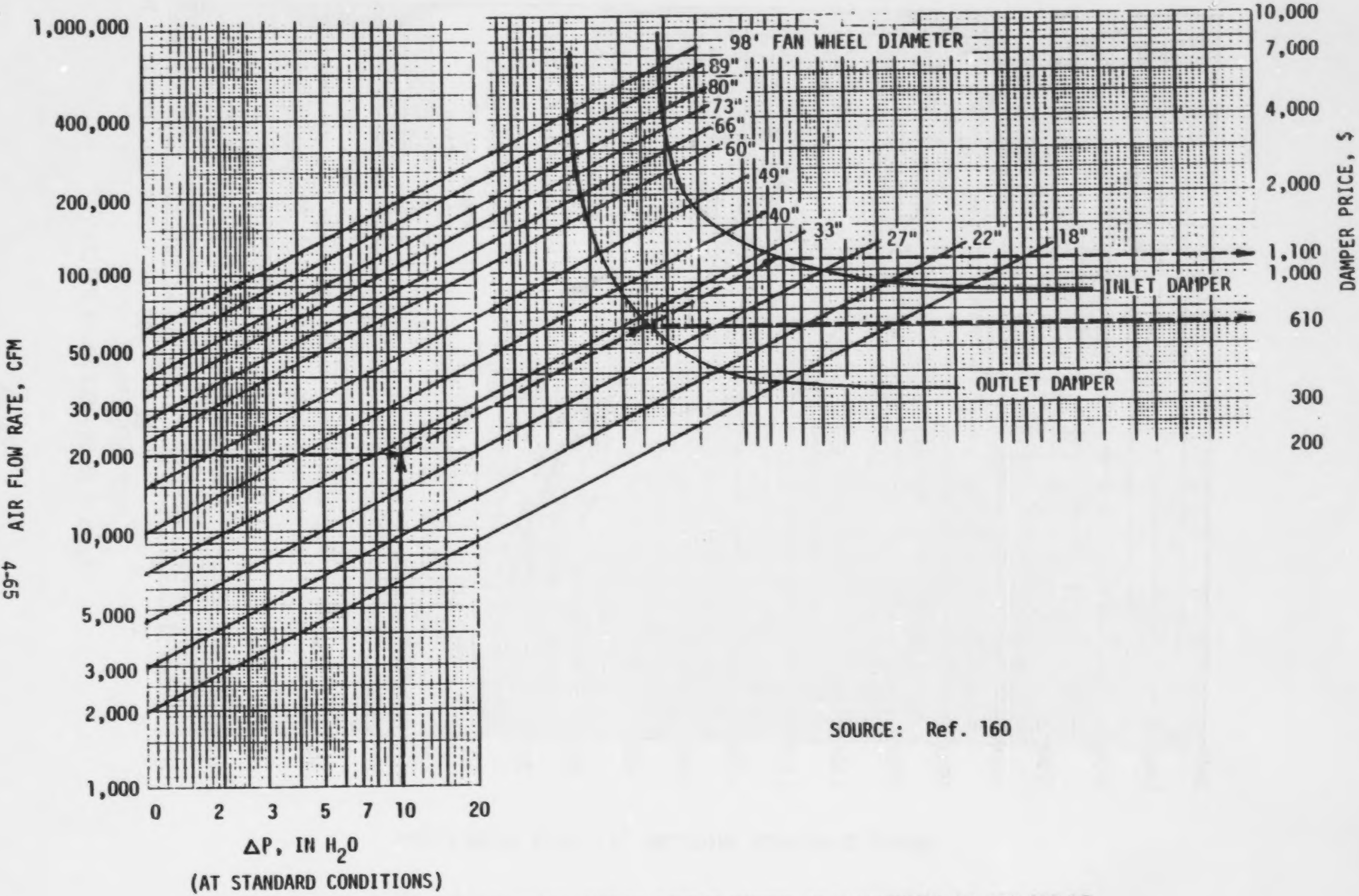
If a magnetic starter is selected, the price is about $450. Prices for motor types other than drip-proof may be estimated using Table 4.8. A totally enclosed motor for this example would cost $700 x 1.5 = $1050. The selection of a motor type may be made from Table 4.9.

For conditions deviating from standard, the following steps must be taken to establish the motor and starter price. Again consider the 300°F application from before.

1. Find the bhp from Figure 4-34 using 50,000 cfm and 15" S.P. = 180 bhp
2. Correct the bhp by multiplying by the fan sizing factor:
   180 bhp x 0.672 - 121 bhp, actual.
3. Find motor and starter prices at 121 bhp. The fan rpm does not require adjustment.

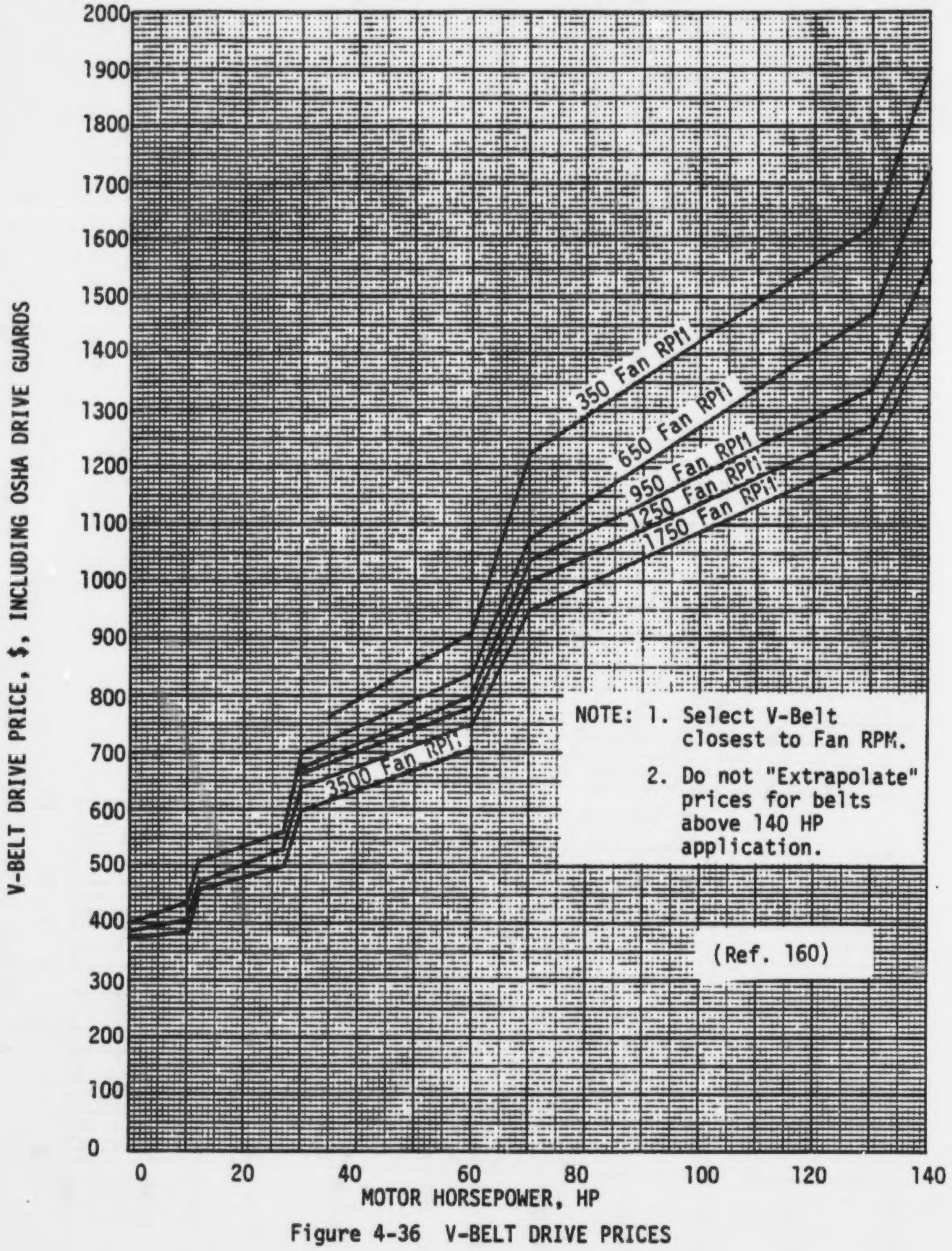
An inlet or outlet damper is usually required on fans, and prices for such are presented in Figure 4-35. Note that the static pressure is measured for standard conditions, as in Figure 4-33 and 4-34. These dampers are supplied by the fan manufacturer and designed to match the inlet and outlet configuration for each fan size.

V-belt drives may be selected for applications where the desired fan speed is not the same as standard motor speeds (nominally 600, 720, 900, 1200, 1800 and 3600 rpm). These drives are used for fan/motor combinations of up to approximately 150 hp. Fan drives above 150 hp are usually direct drives. Figure 4-36 contains prices for V-belt drives as a function of motor bhp and fan rpm. For direct drives, estimate price at 5% of the motor price.



SOURCE: Ref. 160

Figure 4-35 FAN INLET AND OUTLET DAMPER PRICES AS A FUNCTION OF CFM AND ΔP



NOTE: 1. Select V-Belt closest to Fan RPM.

2. Do not "Extrapolate" prices for belts above 140 HP application.

(Ref. 160)

Figure 4-36 V-BELT DRIVE PRICES

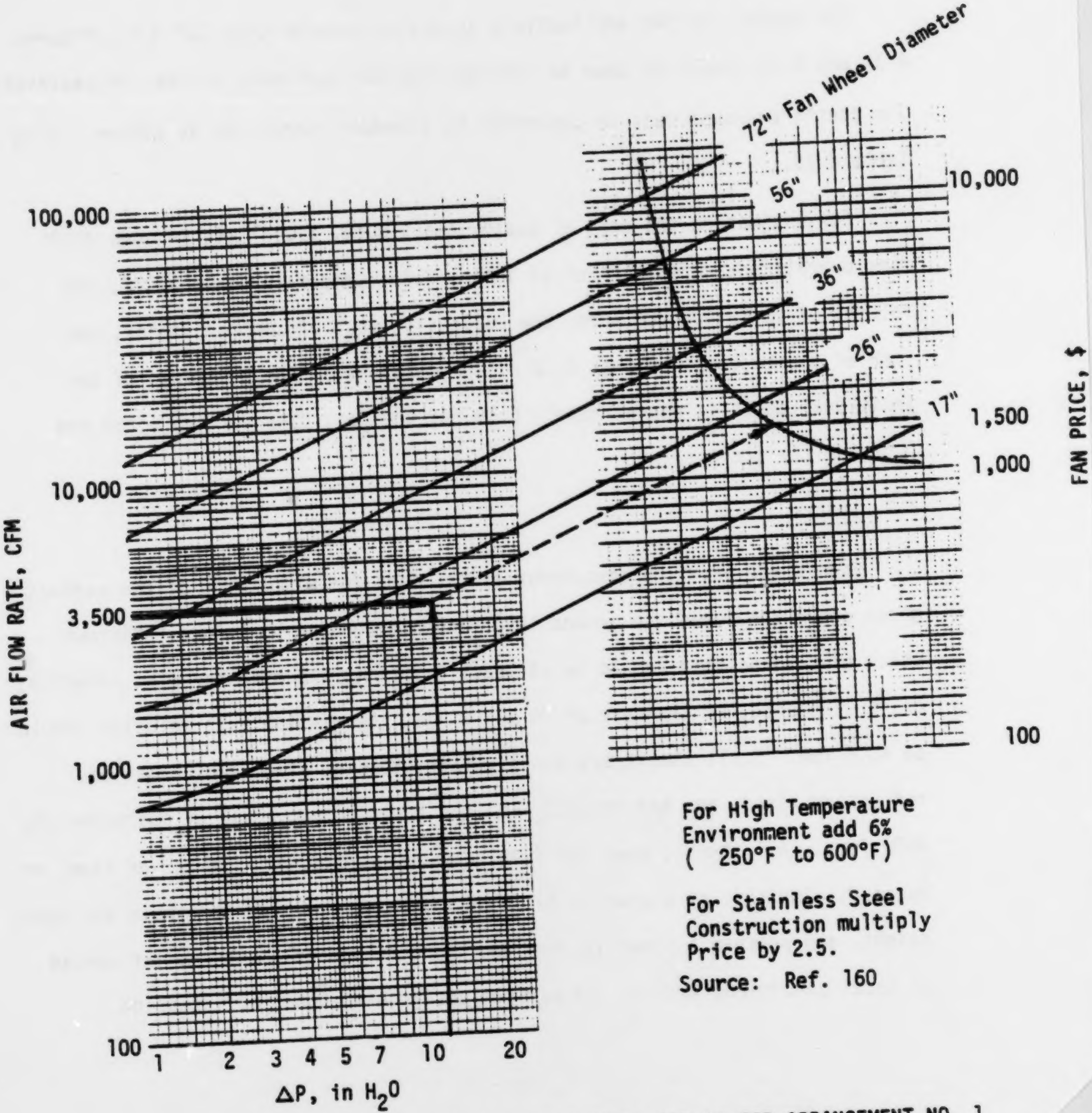
The method of estimating prices for radial tip fans is the same as for backwardly curved fans. Prices for radial tip fans operating under 20" S.P. are given in Figure 4-37. Figure 4-38 provides the data for determining the fan rpm and motor bhp for radial tip fans. Refer to Figure 4-34 to obtain the motor and starter prices once the bhp has been determined.

For radial tip fan applications involving greater than 20" S.P., Figures 4-39 and 4-40 should be used to estimate the fan and motor prices, respectively. The static pressure must be converted to standard conditions as before, using Table 4.10.

For estimating the cost of custom heavy duty, radial tip induced draft fans operating at pressures of 15 inches W.G., temperatures to 250°F, and volumes of up to 400,000 acfm, the collective cost of the fan, motor, and starter can be considered as 0.38 x ACFM delivered. The breakdown of the individual costs is approximately 0.19 for the fan, 0.15 for the motor and 0.04 for the starter.

4.7 Stacks

Stacks are provided downstream of the fans for dispersion of the exhaust gases above the immediate ground level and surrounding buildings. Minimum stack exit velocities should be at least 1.5 times the expected wind velocity; or for instance, in the case of 30 mph winds, the minimum exit velocity should be 4000 fpm. Small stacks are usually fabricated of steel, which may be refractory lined, and are normally limited to exit velocities of approximately 9000 fpm. Tall stacks, over 200 feet, can be designed with liners of steel or masonry. The cost of stacks is based on diameter, material thickness and type, height, and whether a liner is provided. The design of stacks is influenced by local conditions such as the maximum design wind load, soil bearing

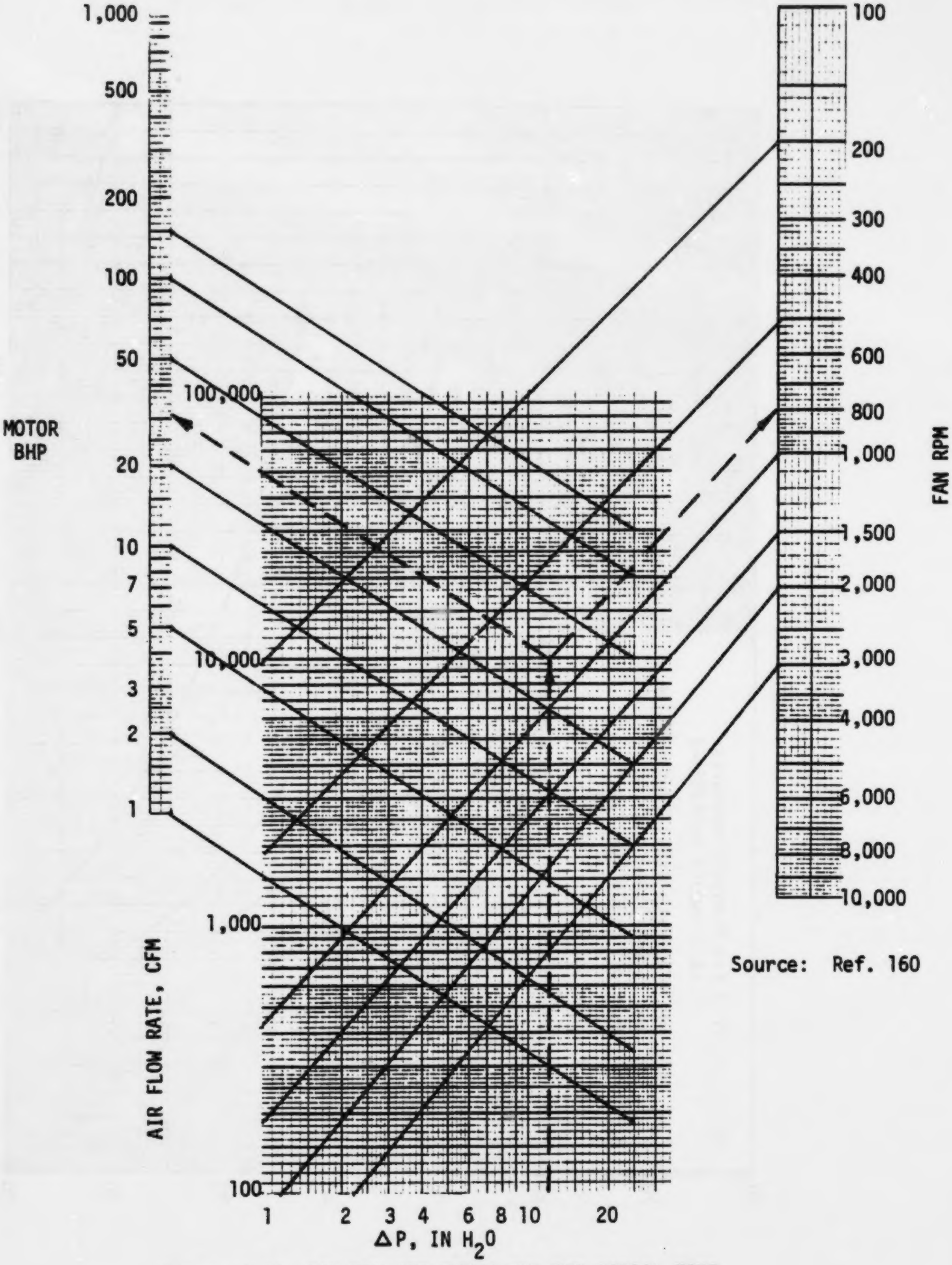


For High Temperature
Environment add 6%
(250°F to 600°F)

For Stainless Steel
Construction multiply
Price by 2.5.

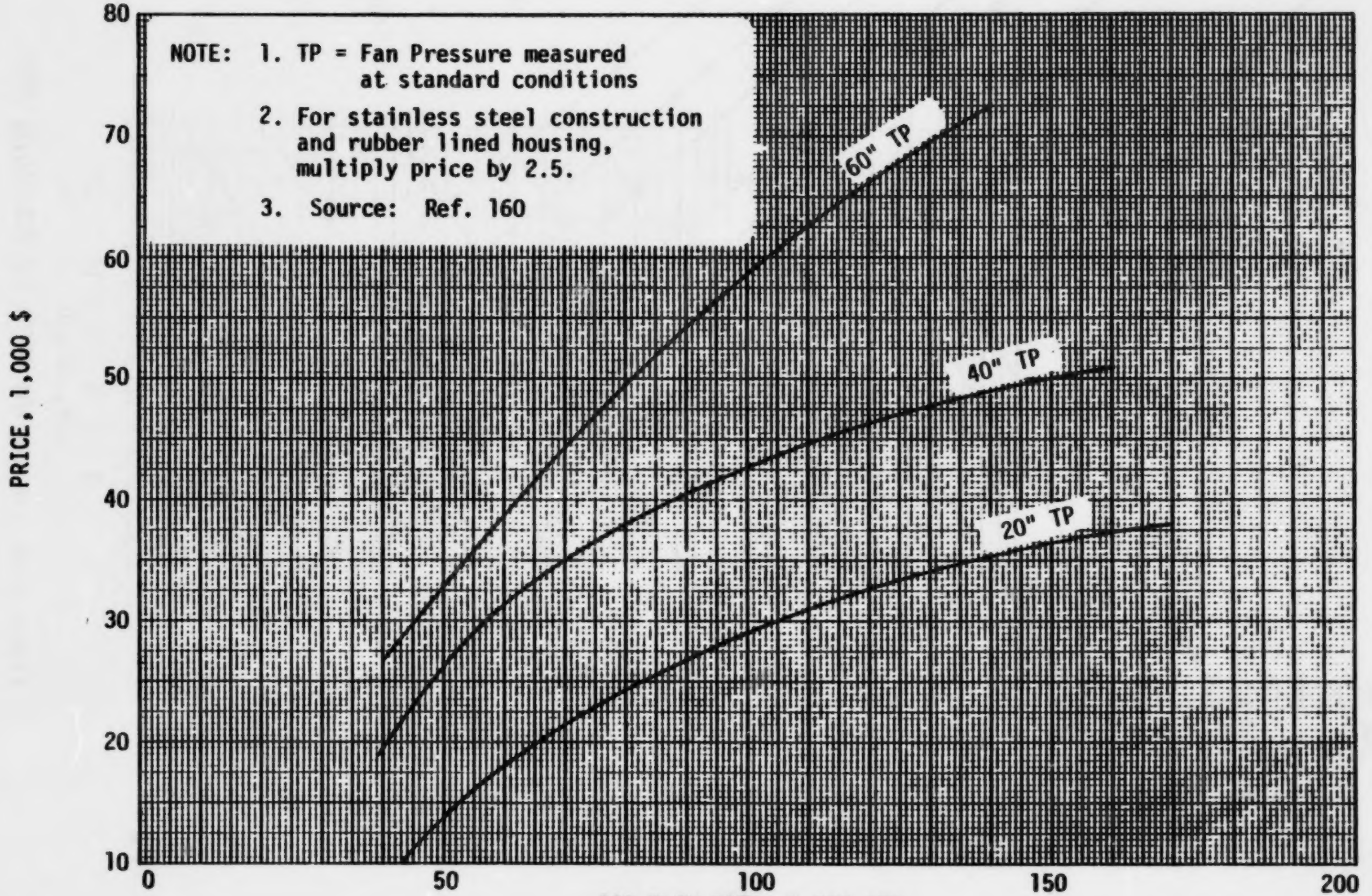
Source: Ref. 160

Figure 4-37 RADIAL FAN PRICES VERSUS ACFM, AND ΔP FOR ARRANGEMENT NO. 1



Source: Ref. 160

Figure 4-38 FAN RPM AND MOTOR BHP FOR RADIAL FANS

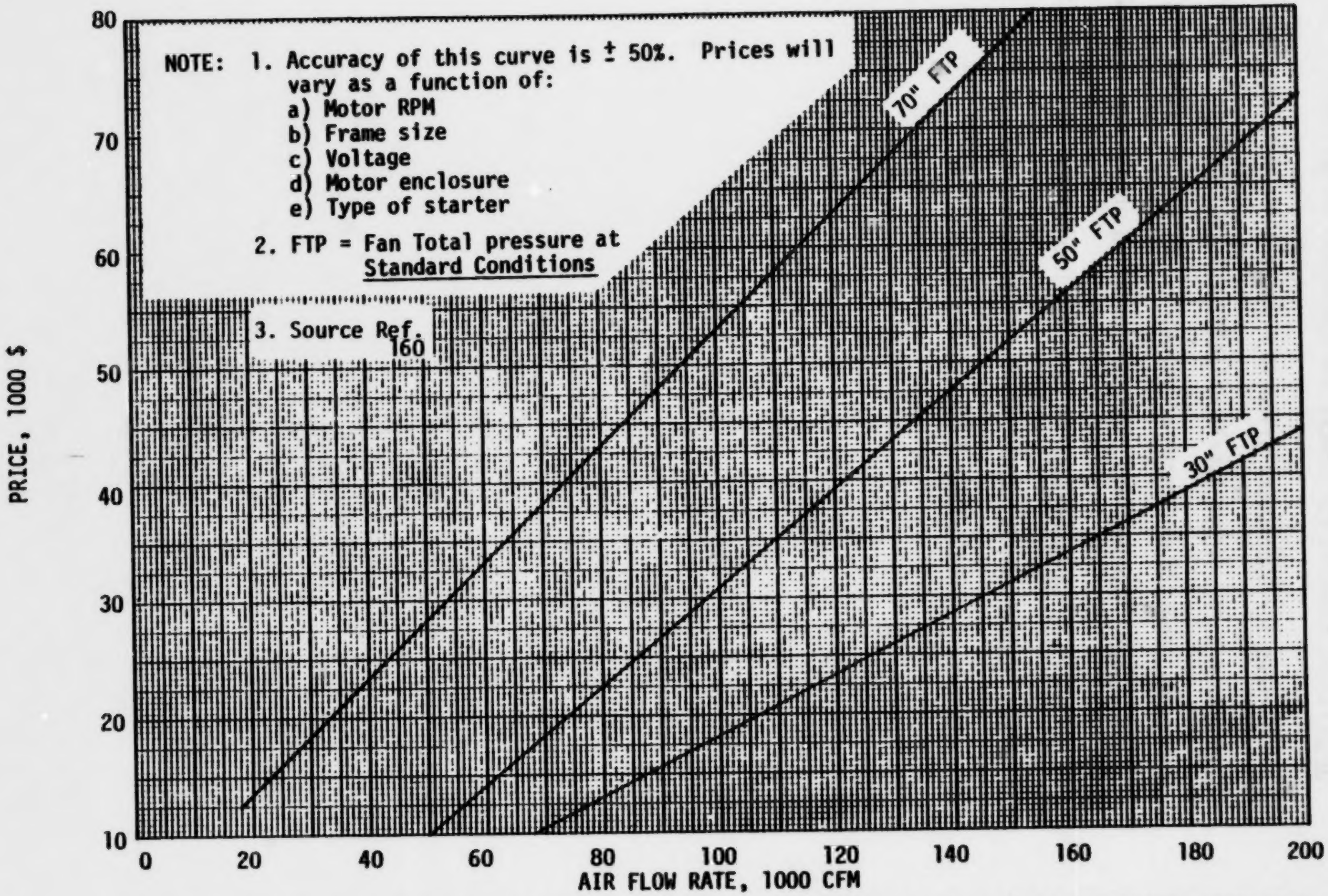


NOTE: 1. TP = Fan Pressure measured at standard conditions

2. For stainless steel construction and rubber lined housing, multiply price by 2.5.

3. Source: Ref. 160

Figure 4-39 RADIAL TIP FAN PRICES



NOTE: 1. Accuracy of this curve is ± 50%. Prices will vary as a function of:
- a) Motor RPM
- b) Frame size
- c) Voltage
- d) Motor enclosure
- e) Type of starter

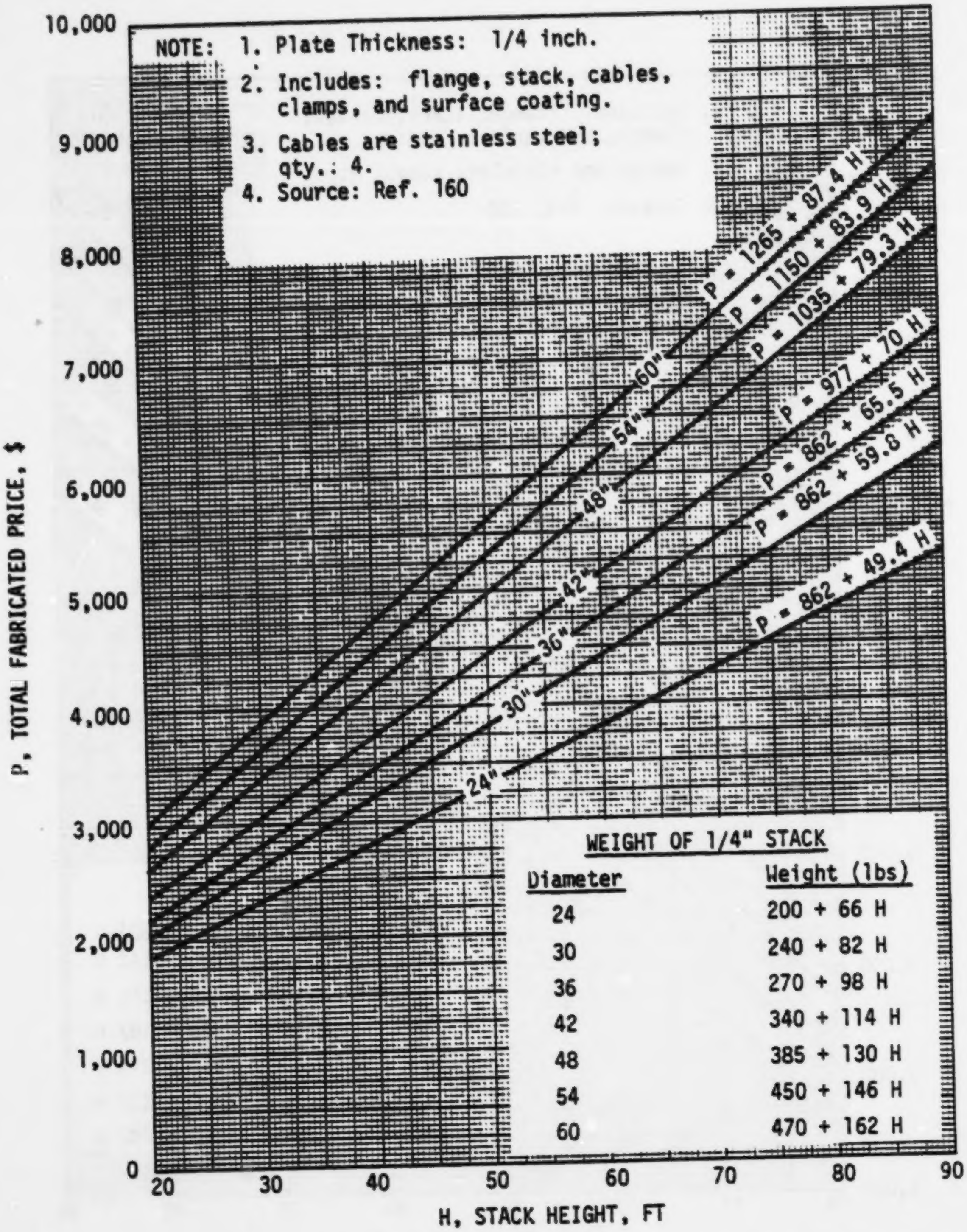
2. FTP = Fan Total pressure at Standard Conditions

3. Source Ref. 160

Figure 4-40 STARTER AND MOTOR PRICES FOR VENTURI SCRUBBER APPLICATIONS (HIGH PRESSURE, HIGH BHP)

characteristics, seismic zone, and building code requirements. Design details and formulas for stacks are contained in ref. 157.

Prices for stacks are given in Figures 4-41, 4-42 and 4-43. Figures 4-41 and 4-42 are for carbon steel, unlined, uninstalled stacks under 100'. These represent the size and range of stacks normally encountered in industrial applications. Figure 4-43 contains installed prices for large diameter stacks over 200 Feet in height with liners and insulation. These stacks are primarily used for large municipal installations such as power plants and incinerators. Cost details are contained in reference 158.

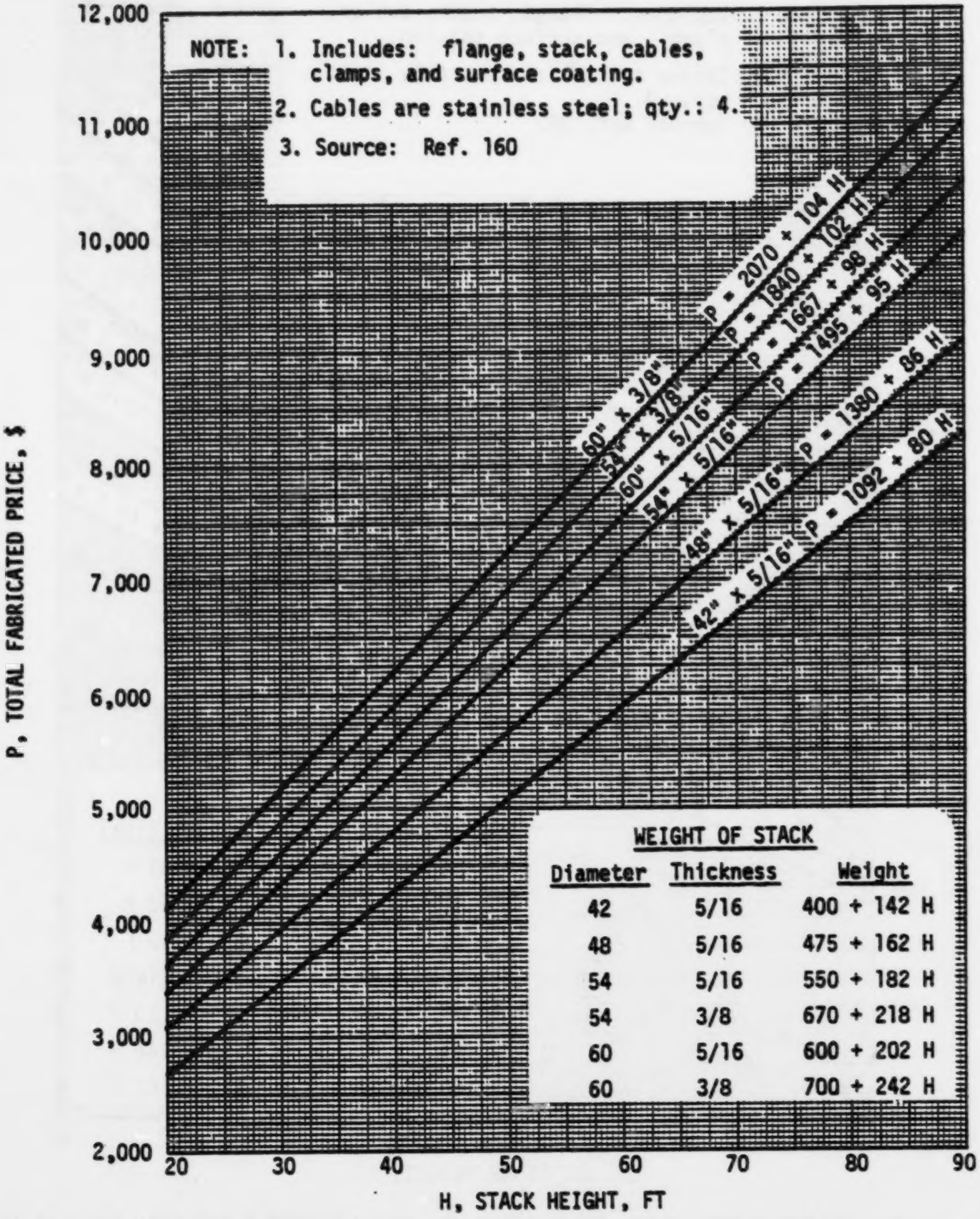


NOTE:
1. Plate Thickness: 1/4 inch.
2. Includes: flange, stack, cables, clamps, and surface coating.
3. Cables are stainless steel; qty.: 4.
4. Source: Ref. 160

WEIGHT OF 1/4" STACK

Diameter	Weight (lbs)
24	200 + 66 H
30	240 + 82 H
36	270 + 98 H
42	340 + 114 H
48	385 + 130 H
54	450 + 146 H
60	470 + 162 H

Figure 4-41 FABRICATED CARBON STEEL STACK PRICE VS. STACK HEIGHT & DIAMETER FOR 1/4 INCH PLATE

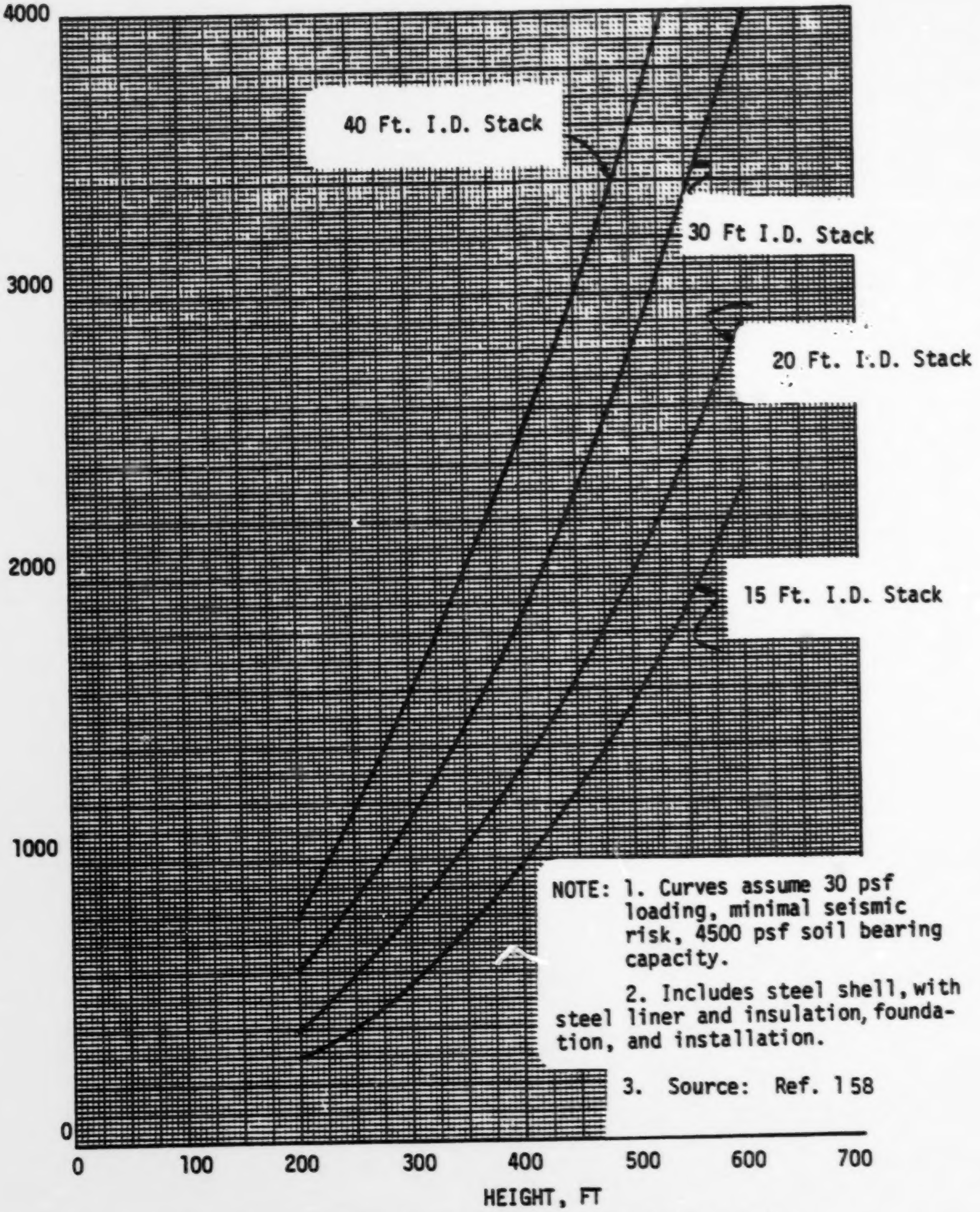


NOTE: 1. Includes: flange, stack, cables, clamps, and surface coating.
2. Cables are stainless steel; qty.: 4.
3. Source: Ref. 160

WEIGHT OF STACK

Diameter	Thickness	Weight
42	5/16	400 + 142 H
48	5/16	475 + 162 H
54	5/16	550 + 182 H
54	3/8	670 + 218 H
60	5/16	600 + 202 H
60	3/8	700 + 242 H

Figure 4-42 FABRICATED CARBON STEEL STACK PRICE VS. STACK HEIGHT & DIAMETER FOR 5/16" & 3/8" P



NOTE: 1. Curves assume 30 psf loading, minimal seismic risk, 4500 psf soil bearing capacity.

2. Includes steel shell, with steel liner and insulation, foundation, and installation.

3. Source: Ref. 158

Figure 4-43 PRICES FOR TALL STEEL STACKS, INSULATED AND LINED

Section 5

CONTROL DEVICES

The following description of the control devices is designed to provide the user with the basic concept of the operation of the device, the parameters required to size and cost it, and the required auxiliary equipment necessary for proper operation of the gas cleaning system. The equipment cost of the control device is based on flange-to-flange costs. The cost of the auxiliary equipment has already been discussed in the preceeding Section 4. In this section, the description of the control devices and the integration of the auxiliary equipment will be discussed so that the user can develop the capital and operating costs of a control system for any particular application.

5.1 High Voltage Electrostatic Precipitators

Gas cleaning by electrostatic precipitation is particularly suited for gas streams which can be easily ionized and which contain either liquid or solid particulate matter. The method of removal consists of passing the particle-laden gas through an electrostatic field produced by a high-voltage electrode and a grounded collection surface. The gas is ionized by the high voltage discharge and the particulate matter is charged by the interaction of the gas ions. The particles migrate to the collecting surface which has an opposite polarity and are neutralized. The adhesive properties of the particles and the action of the electrical field keep the particles on the collecting surface and inhibit re-entrainment. The particles are removed by rappers or by other mechanical devices that vibrate the collector surface and dislodge the particulate, which drops by gravity to hoppers. Usually this is accomplished during normal operation, however, in cases where severe reentrainment is a problem, sections of the precipitator may be isolated during rapping. The particulate matter is removed from the hoppers periodically by either pneumatic or mechanical screw conveyors.

Electrostatic precipitators are used extensively on large volume applications where the fine dust and particulate is less than 10-20 microns in size with a predominant portion in the sub-micron range. The precipitators can achieve high efficiencies (in excess of 99%) depending on the resistivity of the particulate matter and the characteristics of the gas stream. Wet or dry particulate can be collected including highly corrosive materials if the units are suitably constructed. Precipitators can be used at high temperatures (up to 1000°F) but are normally operated at temperatures below 700°F. The static pressure drop through the units is low, usually up to one-half inch W.G., for units operating at normal gas velocities (2-8 feet per second). The initial capital cost of electrostatic precipitators is high; however, operating (utility) and maintenance costs are reasonably low. Safety precautions are always required since the operating voltages are as high as 100,000 volts. The overall size of electrostatic precipitators is comparable to fabric filters (baghouses) and space requirements are an important factor in the layout and design of the facilities.

The cost of the basic electrostatic precipitator is a function of the plate area which, in turn, is a function of the required efficiency. The relationship of the plate area to efficiency can be shown by the Deutsch equation:

$$E = 1 - e^{\left(-w\frac{A}{Q}\right)}$$

where E = collection efficiency

w = drift velocity, fps

A = plate area, ft^2

Q = flow rate, acfs

The Deutsch equation, though adequate for "scope" cost estimates, furnishes only an approximate method to estimate plate area.

The electrical characteristics of the dust, quantified by the drift velocity, as shown in the Deutsch equation, have a large effect on the collection efficiency and plate area, and consequently, on the cost of the precipitator. The resistivity of the dust varies with the temperature and moisture content of the gas, therefore, in some applications, auxiliary equipment may be required to precondition the gas stream prior to entering the precipitator. The addition of moisture in the gas stream together with low operating temperatures will necessitate insulating the precipitator to prevent condensation and subsequent corrosion problems. The cost of the basic precipitator is therefore separated into insulated and non-insulated units. Special cost factors can be incurred in the type of power supply such as automatic voltage control, number of individual sections energized, type of rectifier, etc., and also, in special materials of construction and special plate design.

These factors are additive costs to the basic collector price and represent custom features either required by the process or by the buyer's specifications. For most applications, the cost curves presented in this manual are sufficient.

Figure 5-1 illustrates schematically the types of auxiliary equipment that would be used in a gas cleaning system incorporating electrostatic precipitators. These include the capture device, ductwork, mechanical collectors, coolers, spray chambers, fans, dust removal, and stacks. A heat exchanger or wasteheat boiler may also be used to cool the gases before entering the precipitator. The use of all or only some of this auxiliary equipment will depend on the particular application and pollutant source. In general, all systems will require a capture device, ductwork and a fan. The capture device can be either a round or rectangular hood located near the pollutant source or it can be directly connected to the source as, for instance, a kiln or furnace. These devices are usually refractory lined, water-cooled, or simply fabricated from carbon steel depending on the gas stream temperatures. Refractory or water-cooled capture devices are used where wall temperatures exceed 800°F; carbon steel is used for lower temperatures. The ducting, like the capture device, should be water cooled, refractory or stainless steel for hot processes and carbon steel for gas temperatures below approximately 1150°F (duct wall temperatures <800°F). The ducts should be sized for a gas velocity of approximately 4000 fpm for the average case. Normally, radiant U-tube coolers would not be required unless the gas stream temperature to the precipitator was above approximately 700°F. Even in these cases it may be prudent to use a spray chamber for cooling since the addition of moisture

$$E = 1 - e^{\left(-w\frac{A}{Q}\right)}$$

where E = collection efficiency

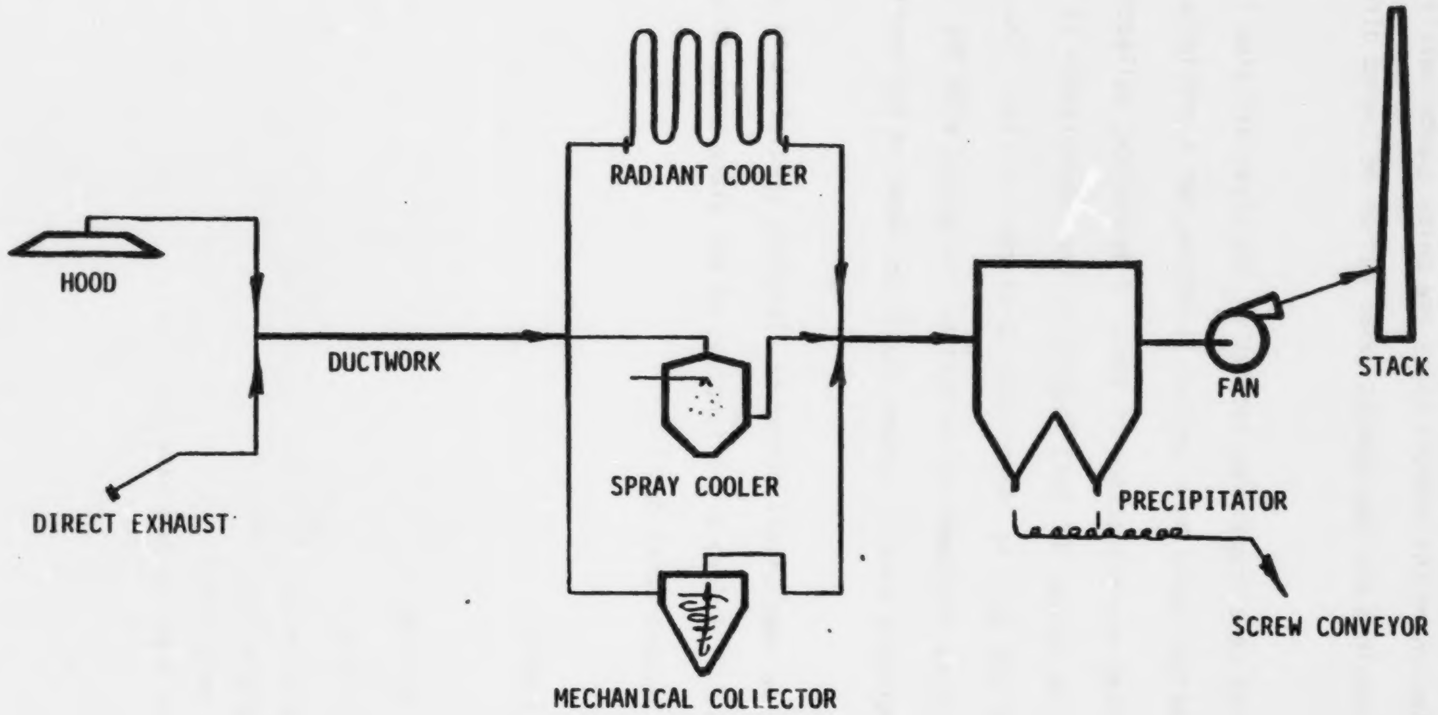
w = drift velocity, fps

A = plate area, ft^2

Q = flow rate, acfs

The Deutsch equation, though adequate for "scope" cost estimates, furnishes only an approximate method to estimate plate area.

The electrical characteristics of the dust, quantified by the drift velocity, as shown in the Deutsch equation, have a large effect on the collection efficiency and plate area, and consequently, on the cost of the precipitator. The resistivity of the dust varies with the temperature and moisture content of the gas, therefore, in some applications, auxiliary equipment may be required to precondition the gas stream prior to entering the precipitator. The addition of moisture in the gas stream together with low operating temperatures will necessitate insulating the precipitator to prevent condensation and subsequent corrosion problems. The cost of the basic precipitator is therefore separated into insulated and non-insulated units. Special cost factors can be incurred in the type of power supply such as automatic voltage control, number of individual sections energized, type of rectifier, etc., and also, in special materials of construction and special plate design.


RADIANT COOLER
HOOD
DUCTWORK
SPRAY COOLER
DIRECT EXHAUST
MECHANICAL COLLECTOR
PRECIPITATOR
FAN
STACK
SCREW CONVEYOR

CONTROL DEVICE AND TYPICAL AUXILIARY EQUIPMENT

Figure 5-1 ELECTROSTATIC PRECIPITATOR CONTROL SYSTEMS

will enhance the precipitation process. Spray chambers may also be required for cold processes where the addition of moisture will improve precipitation. For combustion processes where the exhaust gases are below approximately 700°F, cooling would not be required and the exhaust gases can be delivered directly to the precipitator.

A backwardly-curved centrifugal fan located on the clean air side (downstream of the precipitator) would be a typical selection for a precipitator application handling high concentrations of dust. A mechanical collector in this case may be used to reduce the dust loading on the precipitator if an appreciable portion of the dust is larger than 20 microns in size. The selection and type of auxiliary equipment which must be integrated with the control device to develop a workable control system should be based on engineering judgement.

Prices for dry type (mechanical rapper or vibrator) precipitators are contained in Figure 5-2 . Prices are a function of net plate area, which are calculated using the Deutsch equation:

(1) $\eta = 1 - e^{(-wA/Q)}$

or

(2) $A = -Q \ln (1-\eta)/w$

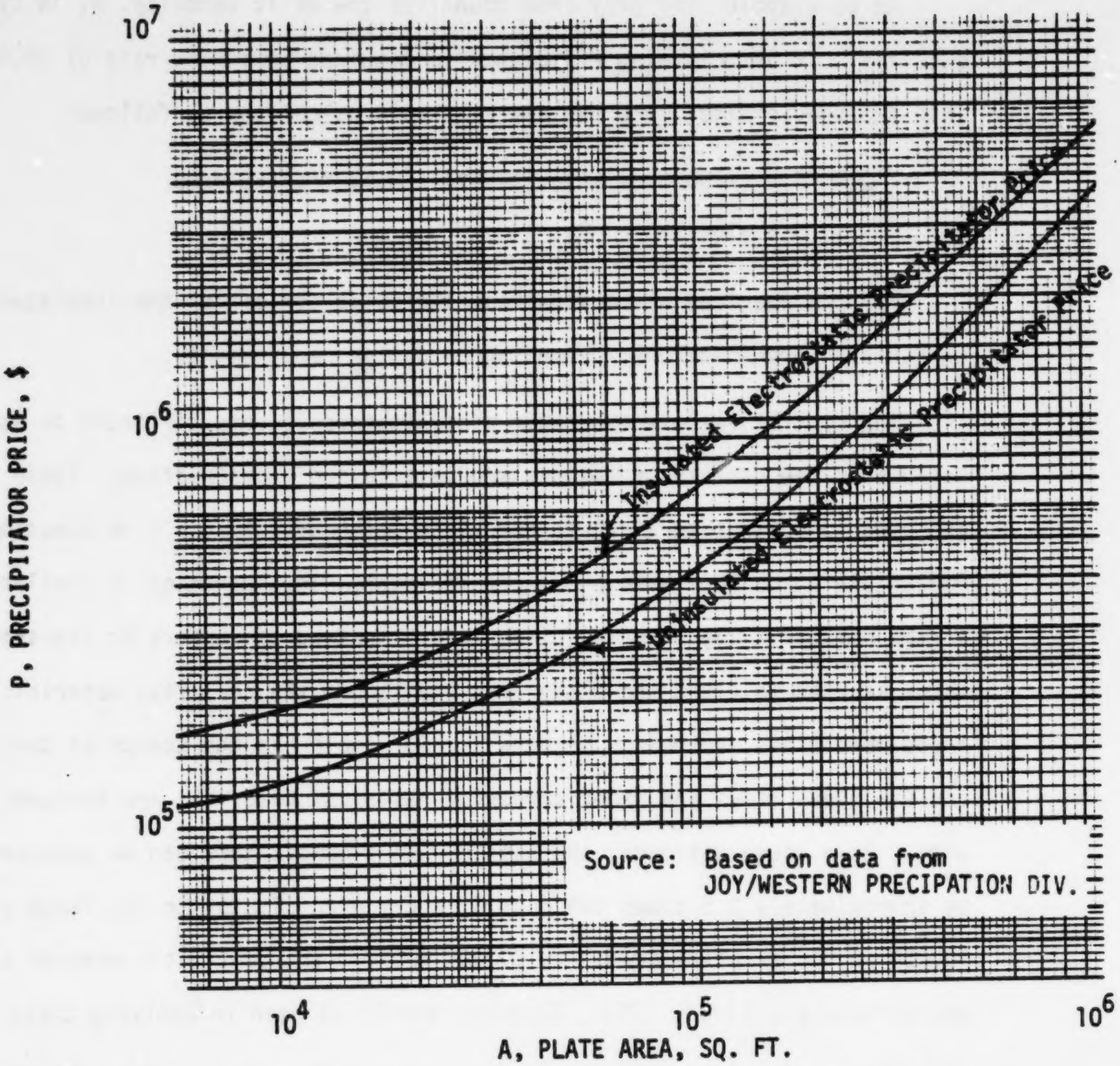
where η is efficiency

w is drift velocity, f/s

A is net plate area, ft^2

Q is flow rate, cfs

exp. is e, the Naperian log base



Source: Based on data from JOY/WESTERN PRECIPITATION DIV.

Figure 5-2 DRY TYPE ELECTROSTATIC PRECIPITATOR PURCHASE PRICES VS. PLATE AREA

As an example, for gray iron foundries the drift velocity, w, is typically 0.12 f/s. If 99% cleaning efficiency is required on a flow rate of 10,000 cfm into the precipitator, the net plate area is calculated as follows:

$$A = (-10000 \text{ cfm})(\ln (1-.99))/(0.12 \text{ f/s})(60 \text{ s/m})$$
$$= 6396 \text{ ft}^2$$

For the required plate area read the price for either the insulated or uninsulated precipitators, depending on design requirements.

The cost of wet electrostatic precipitators is very difficult to estimate because of the variety of designs and materials of construction. These devices are used to collect particulate and mists which are difficult or sometimes impossible to collect with a dry precipitator. The operation is similar except in the method of cleaning the plate area. Instead of rappers or vibrators, water is used to flush the plate area and remove the collected material. Under these conditions, corrosion becomes a major factor in the design of the units and stainless steel and other corrosion resistant materials are frequently used. As a rough estimate, the cost of wet precipitators can be considered to be approximately 2.5 times the cost of a dry precipitator in the range of 20,000 sq.ft. of plate area. At 50,000 sq.ft., the cost ratio reduces to approximately 2.0 (ref. 172). Caution should be used in applying these factors since materials of construction have a large influence on costs. For instance, lead lined plates are used in the collection of acid mists in wet precipitators. The comparative costs of these units is approximately 10 times the cost of a dry precipitator.

5.2 Venturi Scrubbers

Venturi-type scrubbers are capable of providing high efficiency collection of sub-micron dusts which are not easily collected by other types of scrubbers. Basically, the scrubber is constructed with a converging section of the venturi to accelerate the gas stream to a maximum velocity at the throat section where impaction with the scrubbing fluid or liquor occurs. Fine droplets of the scrubbing liquor are atomized as a result of this interaction and the relative velocities between the dust particles and droplets cause collision and agglomeration as they proceed through the throat section. Further agglomeration occurs as the gas stream is decelerated in the diverging section of the venturi, thus producing droplets with the entrapped dust of a size easily removable by mechanical means.

The pressure drop through the venturi is a function of gas stream throat velocity and scrubbing liquor flow rate, which in turn have been chosen for a desired collection efficiency on a given dust. The smaller the dust particle size, the higher the pressure drop required. As the pressure drop is increased, finer droplets are atomized to interact with the dust particles through impingement and agglomeration, with the consequent increase in collection efficiency. Increasing the pressure drop can be accomplished by either increasing the gas stream throat velocity, increasing the scrubbing liquor flow rate or both. The relationship between pressure drop and collection efficiency is the same for all types of venturi scrubbers irrespective of the size, shape or general configuration of the scrubber. Venturi scrubbers are normally operated at pressure drops of between 6 and 80 inches W.G. depending on the characteristics of the dust, and at liquor flow rates of 3 to 20 gpm per 1000 ACFM. The collection efficiencies range from 99+% for one micron or larger sized particles to 90 to 99% for particles below one micron size.

A separator for removal of the agglomerates from the gas stream is provided downstream of the scrubber. These separators are usually of the cyclone type where the gas stream and agglomerates are given a cyclonic motion which forces the liquid and particles to impinge on the walls of the separator by centrifugal force. The separator normally consists of a cylindrical tank with a tangential inlet located at the lower side of the tank and an exhaust outlet located at the top of the tank on the centerline axis. A cone bottom with outlet is provided to collect the liquid slurry. The collected particles settle to the bottom of the cone and are removed to the water treatment facility while the cleaner liquid above the sediment is removed and recycled to the scrubber.

For hot processes, a considerable amount of water is vaporized in the scrubber and upstream equipment (e.g., quencher) which must be handled by the fan. Although the gas volume is reduced, a large portion remains as water vapor which results in higher horsepower requirements and in higher operating costs. To alleviate this condition, a gas cooler can be incorporated into the separator to cool and dehumidify the gas stream. Several types of gas coolers are used for this purpose; one type employs spray banks of cooling water followed by impingement baffles while a second type utilizes flooded plates or trays with either perforated holes or bubble caps to permit passage of the gas stream through the bath of cooling water. Several plates or trays can be used in sequential stages to provide the necessary cooling and contact time.

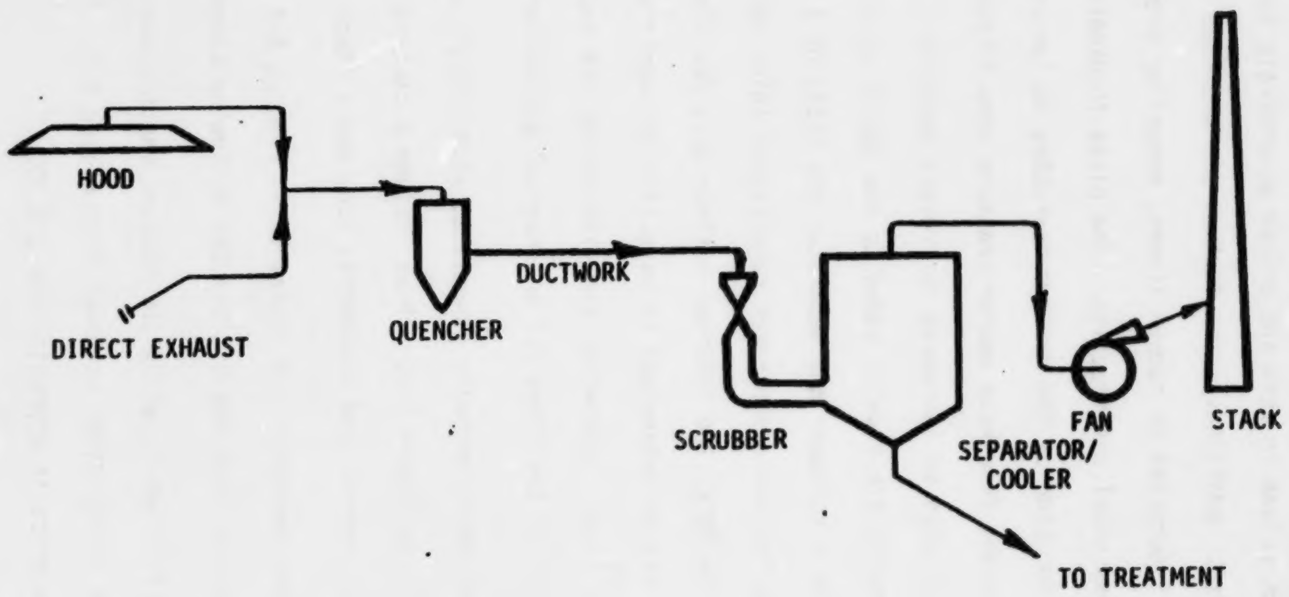
In addition to its ability to remove sub-micron dusts, the venturi scrubber with separator and gas cooler/contactor can also be used as a gas absorber. These units have been used successfully in the removal of acid mists in the chemical industry and the removal of SO_2 and SO_3 in municipal power plant flue gases.

The cost of the scrubber and separator are based on the volumetric flow rate, operating pressure, and materials of construction. The sizes of the scrubber, separator, and elbow (vertically oriented) are determined from the actual inlet gas volume in acfm and priced accordingly for a basic plate thickness of 1/8 inch. Additional cost factors are provided for different metal thicknesses, fiberglass or rubber liners, manual or automatic venturi throat, and stainless steel construction. The plate thickness for the scrubber and separator is a function of the maximum operating design pressure and shell diameter. As the volume flow rate and/or pressure drop increase, the metal wall thicknesses must also be increased to prevent buckling. Some allowances for corrosion or erosion are usually added to the design conditions. Typical design parameters for a scrubber and separator are based on a scrubber inlet gas velocity of 3500 fpm and a separator superficial inlet velocity of 600 fpm. For a given flow rate, the internal surface area for the scrubber, elbow and separator can be determined to establish the additive cost of a rubber or fiberglass liner. Likewise, the diameter of the separator will determine the diameter of the trays for an internal gas cooler.

The auxiliary equipment normally associated with venturi scrubber systems is shown schematically in Figure 5-3. These include a capture device and ductwork, a quencher, dust removal and treatment, fan, and a stack.

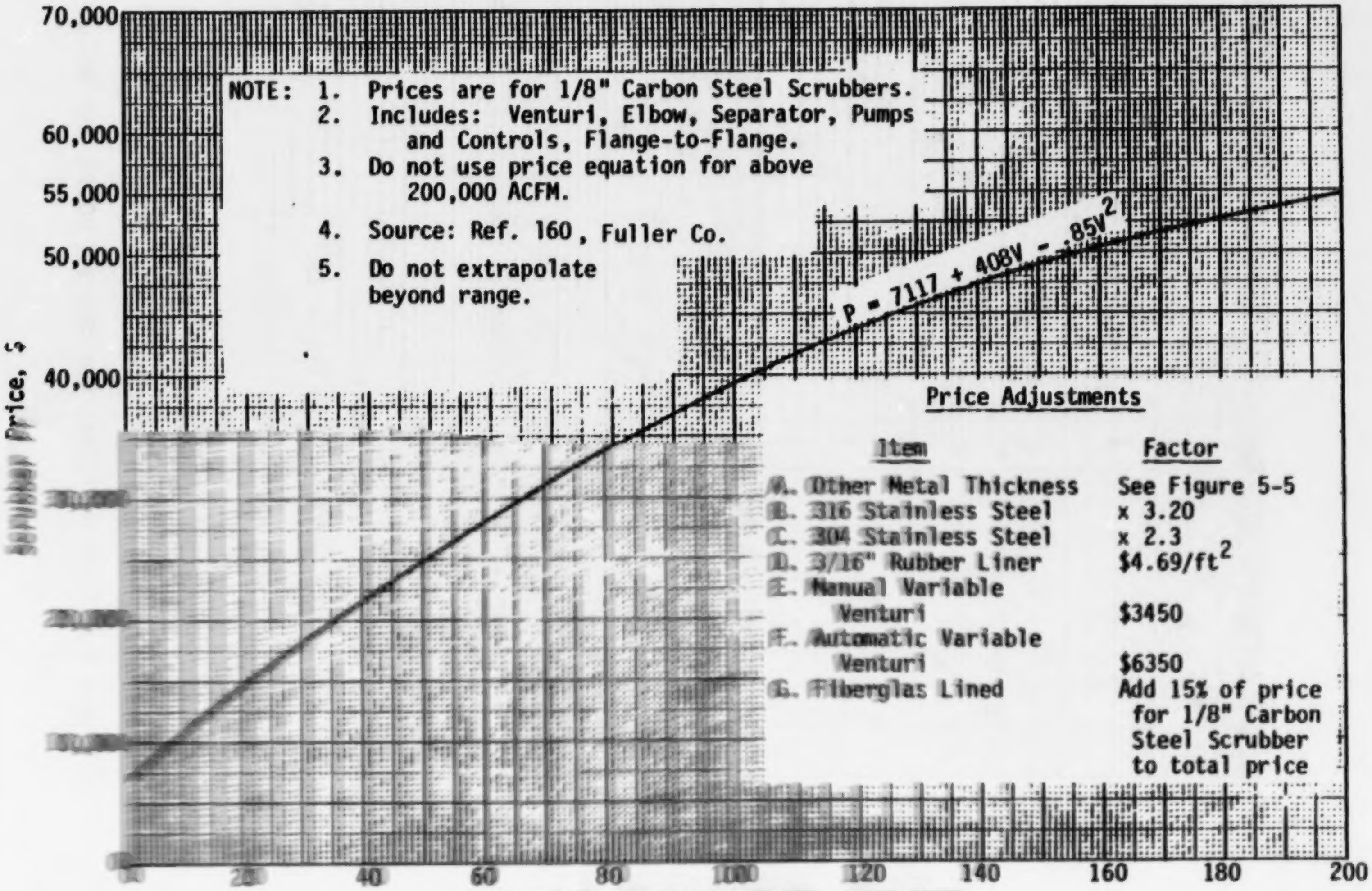
Prices for venturi scrubbers are contained in Figures 5-4 through 5-8. To price a scrubber using these curves, use the following steps.

A. Determine the gas volume entering the venturi section and read the price for a 1/8" thick carbon steel scrubber from Figure 5-4. For example, at 100,000 ACFM the price is approximately $39,000.


HOOD
DIRECT EXHAUST
QUENCHER
DUCTWORK
SCRUBBER
SEPARATOR/
COOLER
FAN
STACK
TO TREATMENT

CONTROL DEVICE AND TYPICAL AUXILIARY EQUIPMENT

Figure 5-3 VENTURI SCRUBBER CONTROL SYSTEMS



NOTE:
1. Prices are for 1/8" Carbon Steel Scrubbers.
2. Includes: Venturi, Elbow, Separator, Pumps and Controls, Flange-to-Flange.
3. Do not use price equation for above 200,000 ACFM.
4. Source: Ref. 160, Fuller Co.
5. Do not extrapolate beyond range.

Price Adjustments

Item	Factor
A. Other Metal Thickness	See Figure 5-5
B. 316 Stainless Steel	x 3.20
C. 304 Stainless Steel	x 2.3
D. 3/16" Rubber Liner	$4.69/ft^2
E. Manual Variable Venturi	$3450
F. Automatic Variable Venturi	$6350
G. Fiberglas Lined	Add 15% of price for 1/8" Carbon Steel Scrubber to total price

Figure 5-4 1/8" THICK CARBON STEEL FABRICATED SCRUBBER PRICE VS. VOLUME

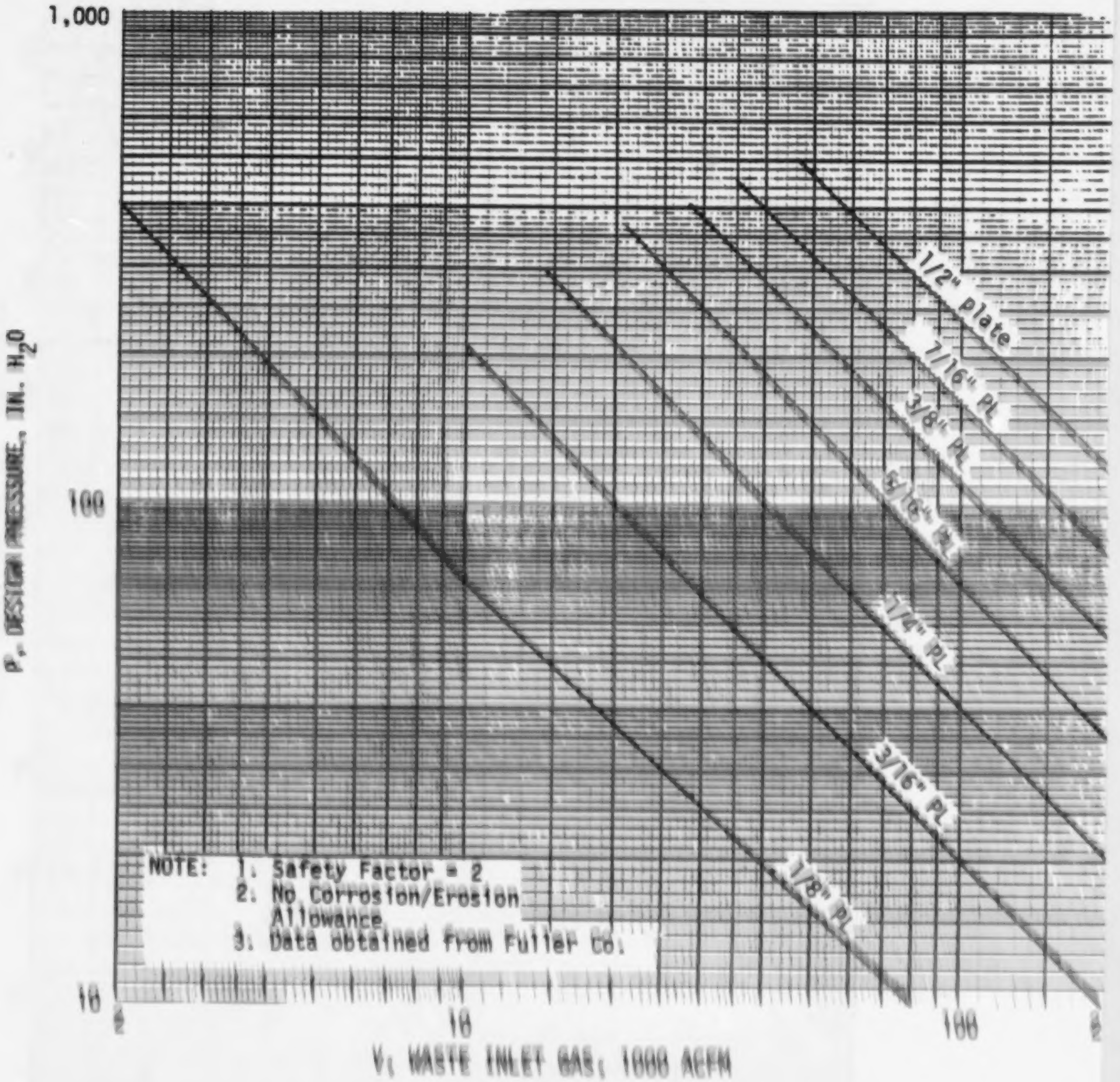
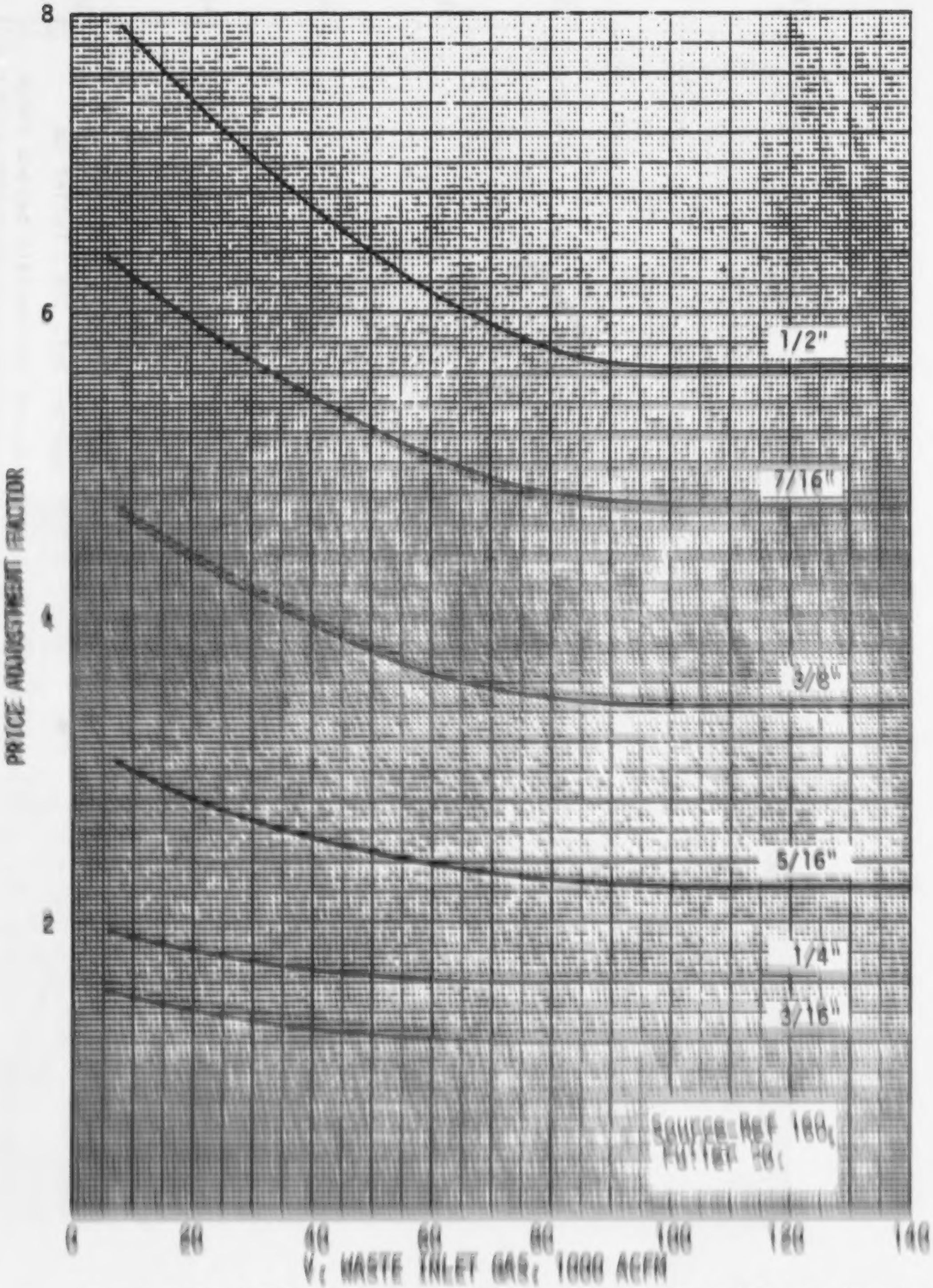
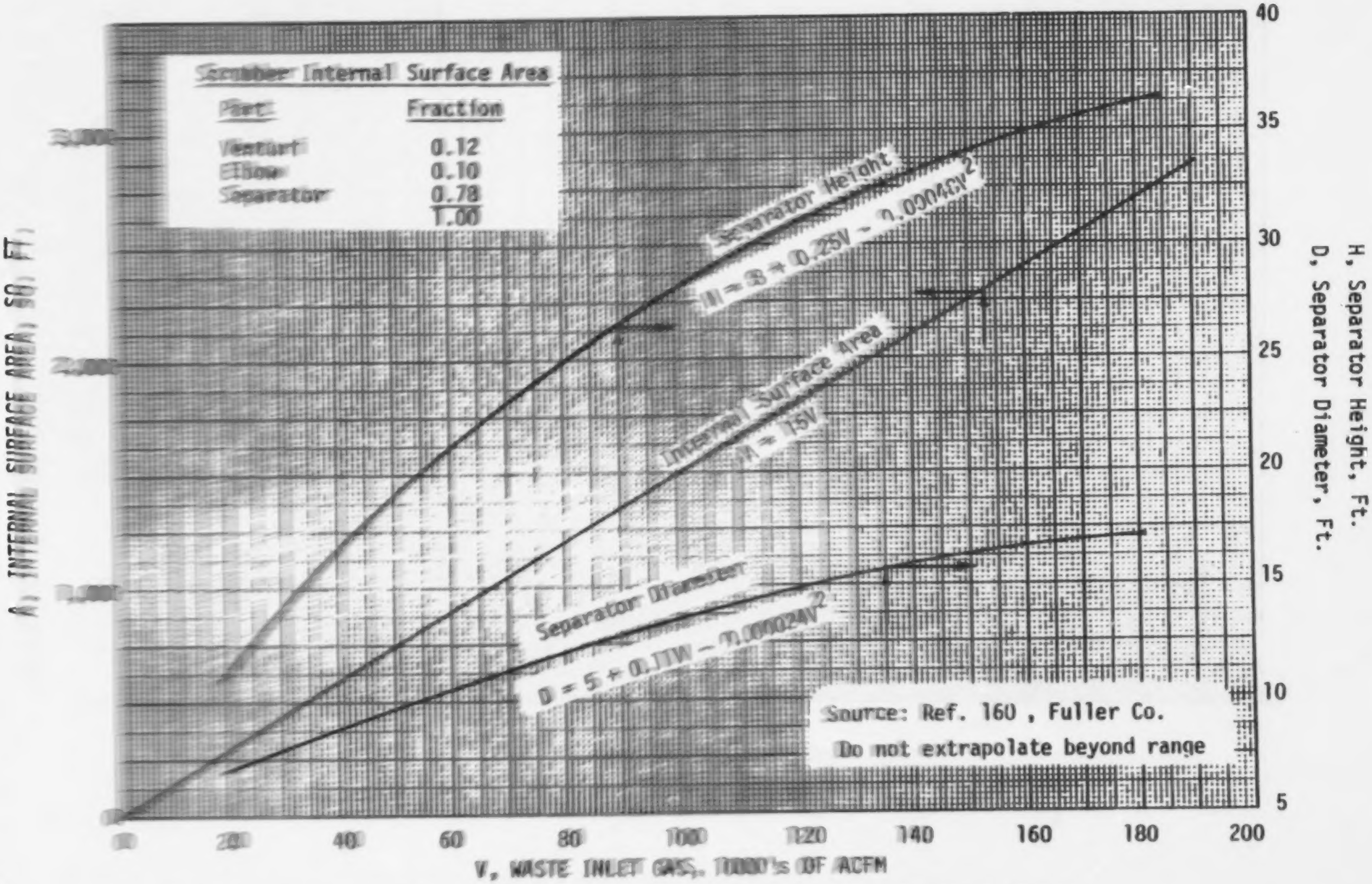


Figure 5-5 METAL THICKNESS REQUIRED VS. VOLUME AND DESIGN PRESSURE



Source: Ref 160, Fuller 50,

Figure 5-6 PRICE ADJUSTMENT FACTORS VS. PLATE THICKNESS AND VOLUME



Scrubber Internal Surface Area

Part	Fraction
Venturi	0.12
Elbow	0.10
Separator	0.78
	1.00

Source: Ref. 160, Fuller Co.

Do not extrapolate beyond range

Figure 5-7 SCRUBBER INTERNAL SURFACE AREA AND SEPARATOR DIAMETER AND HEIGHT VS. WASTE INLET GAS VOLUME

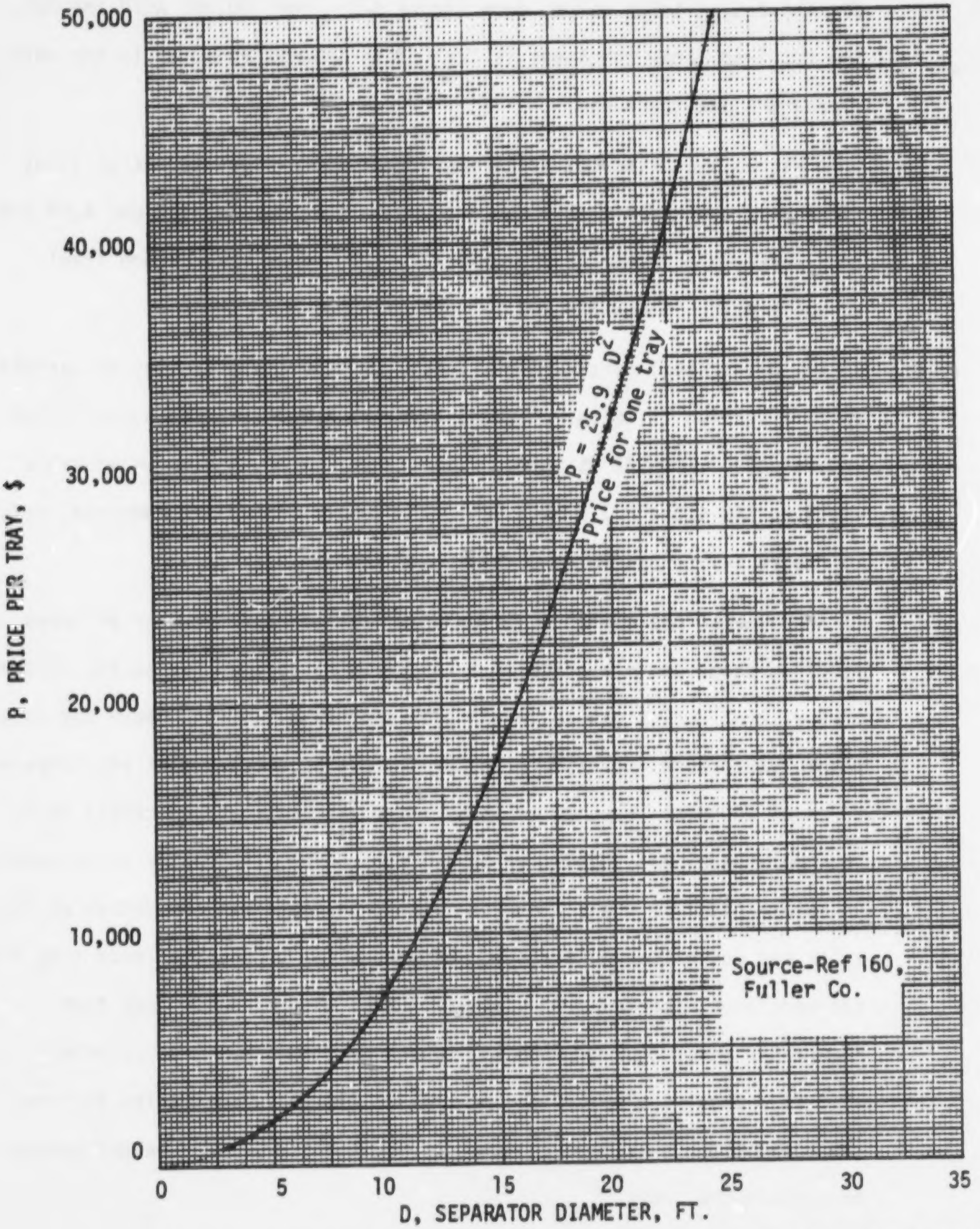


Figure 5-8 INTERNAL GAS COOLER BUBBLE TRAY COST VS. SEPARATOR DIAMETER

B. Determine the pressure drop across the scrubber required to obtain the desired efficiency (see Table 2.2) and find the required metal thickness for the design inlet volume from Figure 5-5. For 100,000 ACFM and 30", the required metal thickness is 1/4" plate (always round up to the next standard plate thickness).

C. From Figure 5-6, find the price adjustment factor for the design inlet volume and the material thickness found in Step B. For 100,000 ACFM and 1/4" plate, the factor is approximately 1.6. Thus, the carbon steel scrubber price is now $39,000 x 1.6 = $62,400.

D. If stainless steel construction, rubber or fiberglass lining, or variable venturi section is to be included, refer to Figure 5-4 and adjust price accordingly. For 304 stainless steel construction, the adjusted price would be $62,400 x 2.3 = $143,520. If rubber linings are required, refer to Figure 5-7 to determine total square footage.

E. If an internal gas cooler is to be used, determine the number of trays required based on an average of 5 lbs of water removed per sq.ft. of tray area with an outlet gas temperature of approximately 40°F above the inlet water temperature (this is valid for typical scrubber outlet gas temperatures of 200°F or less, water spray temperatures of approximately 70°F, and superficial gas velocities of 600 fpm). The total water to be removed is determined from the difference between the absolute humidities of the inlet and outlet gas conditions. Determine the diameter of each tray from the separator diameter of Figure 5-7. Read the price per tray from Figure 5-8. For 100,000 ACFM the separator diameter is approximately 13.5 ft.; thus, the price for one tray is $14,000. This price includes the cost of the tray plus the cost of additional separator height needed to contain the tray.

NOTE: Radial tip fans are commonly used with scrubbers.

5.3 Fabric Filters

Gas cleaning by fabric filtration is suited for applications where dry particulates are handled or where water in the process gases is in the vapor state The basic filter collector or "baghouse" is capable of operating in excess of 99% efficiency, although satisfactory operation of the system is contingent upon the characteristics of the gas stream and the particulate matter being removed. Basically, the unit consists of compartments containing rows of filter bags or tubes. The particle-laden gas is ducted to each compartment where the gas passes through the bags while the particles are retained on the surface of the bags (the particulate may be retained on either the inside or the outside of the bags). The pressure drop across the filter medium increases as the particulate collects on the fabric until a preset time limit is reached, at which time a section is isolated and the entrapped material is dislodged and collected in hoppers located below the filtering area. Baghouses are characterized by the methods and frequency of bag cleaning. These methods of cleaning are generally referred to as: 1) shaker type, 2) reverse air, and 3) pulse jet.

The shaker type method of cleaning consists of hanging the bags on an oscillating framework driven by a motor with a timer. The baghouse is separated into several compartments so that at periodic intervals, the gas flow to a compartment is interrupted and the motors and connected frames in the compartment are activated with the subsequent shaking of the bags to remove the particulate. The shaker type mechanisms produce a violent action on the bags and, in general, produce more wear on the bags than other types of cleaning mechanisms. For this reason, shaker type cleaning is used in conjunction with heavier and more durable fabric materials.

The reverse air method of cleaning the bags is accomplished by passing air countercurrent to the direction of the gas flow in normal filtration when the compartment is isolated for cleaning. The reverse air is supplied by a separate fan or in some cases, the pressure differential across the bags can be used to collapse the bags without the aid of a fan. This type of cleaning is used with fragile bags (such as fiberglass) or lightweight bags and usually results in longer life for the bag material.

Bag cleaning by pulse jet is accomplished by the use of compressed air jets located at the top of the bags. Periodically, a blast of compressed air is issued down the bag, rapidly expanding the bag to dislodge the particulate. In some cases, this method of cleaning does not require the isolation of the bags to be cleaned from the filtering process so that extra compartments required for cleaning with the shaker and reverse air type baghouses are not needed. In addition, the pulse jet baghouses can sustain higher filtering velocities through the filter medium (higher air-to-cloth ratios) and therefore the overall size of the baghouse is reduced.

Baghouses are also categorized as to the type of service and frequency of bag cleaning and referred to as either intermittent or continuous duty. Intermittent baghouses are cleaned after filtering is completed, i.e., after the process stream is secured or shut down, usually at the end of each day. These baghouses operate with low dust loadings since they cannot be cleaned while on stream. Continuous baghouses operate indefinitely and cleaning of a portion of the filter occurs at periodic intervals while the process gases are being filtered by the remaining filter area. Continuous duty baghouses are more expensive than the intermittent type due to the accessories required in the cleaning process and the additional filter area required for continuous cleaning.

The location of the baghouse with respect to the fan in the gas stream is also a factor in the capital costs. Suction type baghouses, located on the suction side of the fan, must withstand high negative pressures and therefore are more heavily constructed and reinforced than baghouses located downstream of the fan (pressure baghouse). The negative pressure in the baghouse can result in the infiltration of outside air which can result in condensation, corrosion or even explosions if combustible gases are being handled. In the case of toxic gases, this inward leakage can have an advantage over the pressure type baghouse, where leakage is outward. The main advantage of the suction baghouse is that the fan handling the process stream is located at the clean gas side of the baghouse. This reduces the wear and abrasion on the fan and permits the use of more efficient fans (backwardly curved blade design). However, since the exhaust gases from each compartment are combined in the outlet manifold to the fan, the location of compartments with leaking bags is difficult to determine and adds to the cost of maintenance. The outlet manifold from the baghouse is connected to the fans, usually located at ground level, and a stack is normally required to vent the gas from the fans.

Pressure-type baghouses are generally less expensive since the housing must only withstand the differential pressure across the baghouse. Maintenance is also reduced since the compartments can be entered and leaking bags can be observed with reasonable comfort while the compartment is in service. With a pressure baghouse, the housing acts as the stack to contain the fumes with the subsequent discharge at the roof of the structure. The main disadvantage of the pressure-type baghouse is that the fan is exposed to the dirty gases where constant abrasion and wear may become a problem.

The design and construction of baghouses are separated into two groups: standard and custom. Standard baghouses are pre-designed and built as modules which can be operated singly or combined to form units for larger capacity applications. The custom or structural baghouse is designed specifically for an application and is usually built to the specifications prescribed by the customer. The cost of the custom baghouse is much higher than the standard and is used almost exclusively in large capacity (large volume) applications. The advantages of the custom baghouse are many and are usually directed towards ease of maintenance, accessibility, and other customer preferences. In standard baghouses, a complete set of bags are usually replaced in a compartment at one time because of the difficulty in locating and replacing single leaking bags, whereas, in custom baghouses, single bags are accessible and can be replaced one at a time as the bags wear out.

The type of filter material used in baghouses is dependent on the specific application in terms of chemical composition of the gas, operating temperature, dust loading, and the physical and chemical characteristics of the particulate. A variety of fabrics, either felted or woven, are available and the selection of a specific material, weave, finish, or weight is based primarily on past experience. The type of cloth will generally dictate the type of bag cleaning mechanism to be used in the baghouse. Usually, felted fabrics use pulse jet cleaning whereas woven fabrics use mechanical shaker or reverse air cleaning. The type of yarn (filament, spun, or staple), the yarn denier, and twist are also factors in the selection of suitable fabrics for a specific application. Because of the violent agitation of mechanical shakers, spun or staple yarn fabrics of heavy weight are usually used with this type of cleaning. Filament yarn fabrics of lighter weight are employed with reverse air cleaning. The type of material will dictate the maximum operating gas temperature for the baghouse. Nominal operating temperatures for various fabrics are listed as follows (ref. 20):

COTTON: 180°F
POLYPROPYLENE: 180°F
NYLON: 200°F
ACRYLIC: 275°F
POLYESTER: 275°F
NOMEX: 425°F
TEFLON: 500°F
FIBERGLASS: 550°F

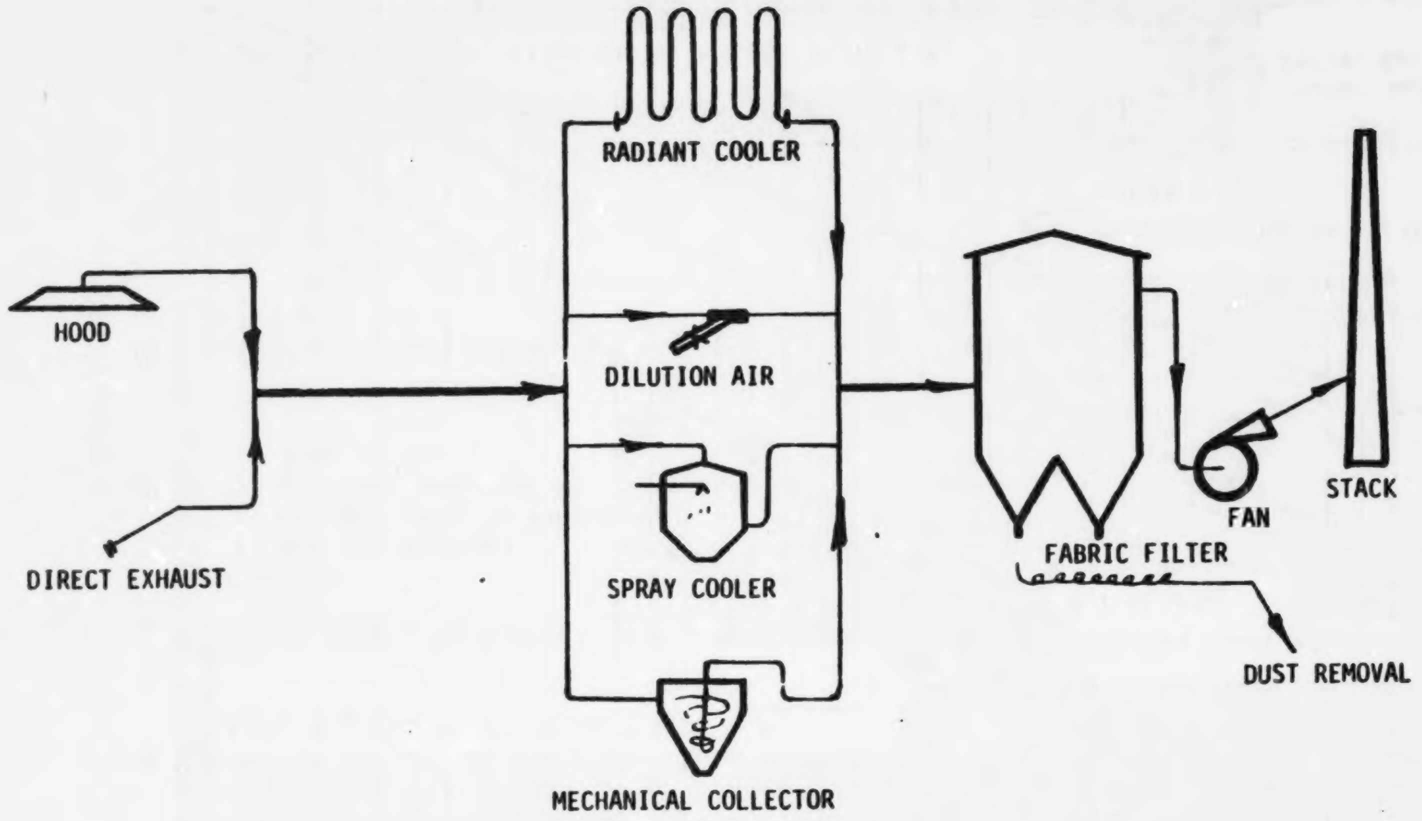
The superficial face velocity of gas passing through the cloth affects pressure drop and bag life. The fundamental filtering parameters are based on this velocity which is equal to the total actual volumetric flow rate in cubic feet per minute divided by the net cloth area in square feet. This ratio is referred to as the air-to-cloth ratio and is the basis for sizing and costing baghouses. High air-to-cloth ratios will reduce the size of the baghouse (and subsequent cost) while low air-to-cloth ratios will require larger units. The air-to-cloth ratio will also determine the type of cleaning mechanism to be used in the baghouse. Shaker type and reverse air cleaning can be used withair-to-cloth ratios of up to 4 to 1 while pulse jet cleaning can be utilized with air-to-cloth ratios of up to 10 to 1 or higher in special cases. The type of material selected as the filtering fabric will also dictate the range of air-to-cloth ratios to be used in a particular application. For instance, polyester fabrics are normally used with ratios of up to 3 to 1, while fiberglass is usually limited to 2 to 1. These limiting ratios are the normal "rule of thumb"; however, with light dust loading, these air-to-cloth ratios can be exceeded in some cases.

The cost reference for baghouses is based on the net cloth area. Net cloth area is defined as the total filter area available for on-stream filtration exclusive of the filter area in compartments which are isolated for cleaning (in the case of intermittent filters, the net cloth area is actually the gross cloth area). The net cloth area is determined by the air-to-cloth ratio recommended for a particular application, which is principally based on the type of fabric, type of dust, carrier gas composition, and the dust concentration. The cost options of the fabric filter are therefore based on the following parameters as determined by the type of application.

1) Type of fabric and air-to-cloth ratio.
2) Intermittent or continuous duty.
3) Pressure or suction type construction.
4) Standard or custom design.
5) Type of cleaning mechanism.
6) Materials of construction.

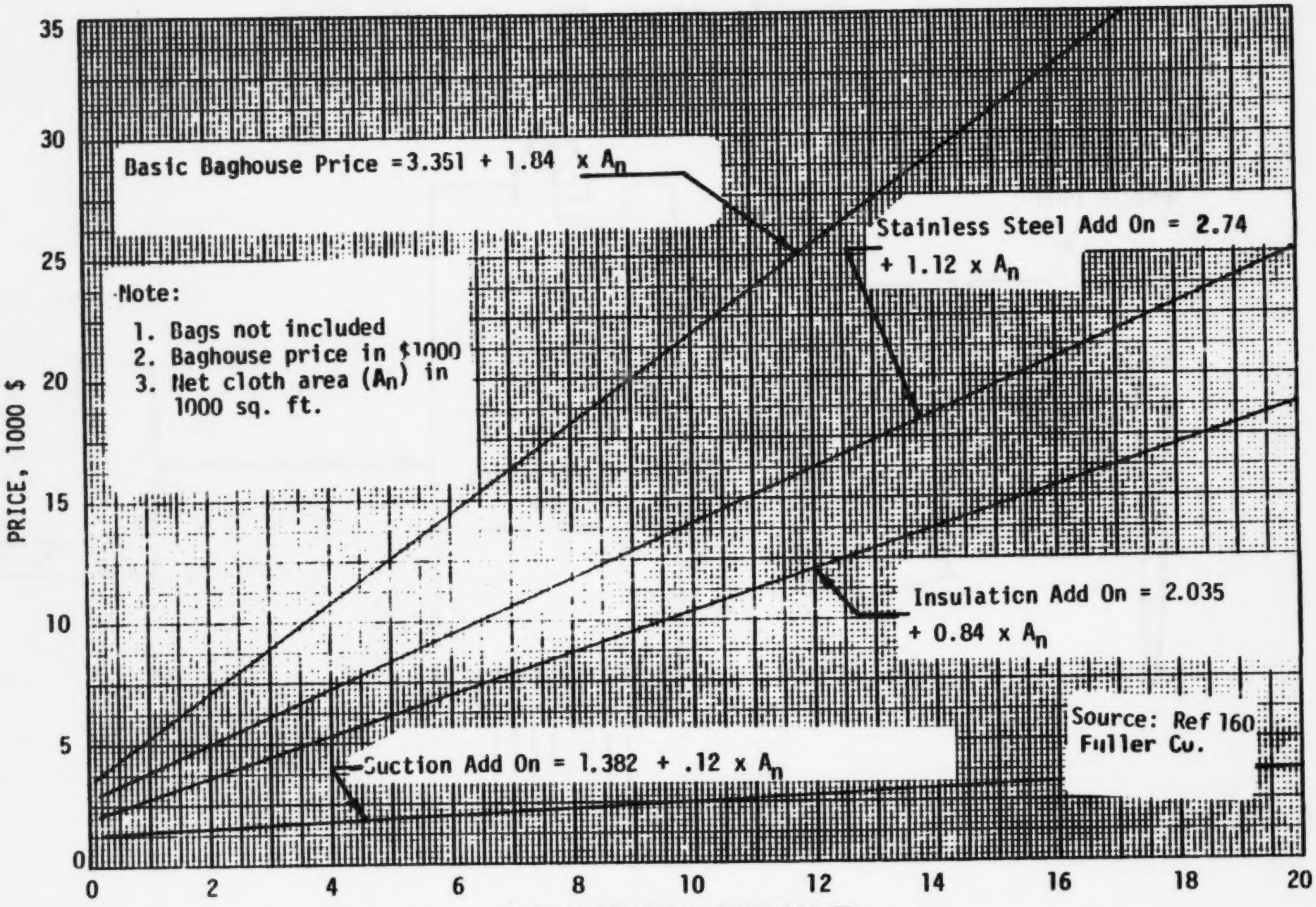
The typical auxiliary equipment associated with fabric filter systems is shown schematically in Figure 5-9. This equipment includes the capture device, ductwork, radiant coolers, spray chambers, dilution air ports, mechanical collectors, dust removal equipment, fans, and stack.

Prices for mechanical shaker, pulse-jet, reverse-air, and custom fabric filters (baghouses) are contained in Figures 5-10 through 5-14. Prices are based on net cloth area, which is calculated by dividing the gas volume entering the baghouse by the required air-to-cloth (A/C) ratio (see Table 2.2). For example, to handle 100,000 ACFM at an A/C = 2.0 requires 50,000 ft^2 net cloth area. The price for a reverse-air, pressure-type baghouse at 50,000 ft^2 is $176,000. For stainless steel construction, insulation, and suction-type


RADIANT COOLER
HOOD
DILUTION AIR
DIRECT EXHAUST
SPRAY COOLER
MECHANICAL COLLECTOR
FABRIC FILTER
FAN
STACK
DUST REMOVAL

CONTROL DEVICE AND TYPICAL AUXILIARY EQUIPMENT

Figure 5-9 FABRIC FILTER CONTROL SYSTEMS

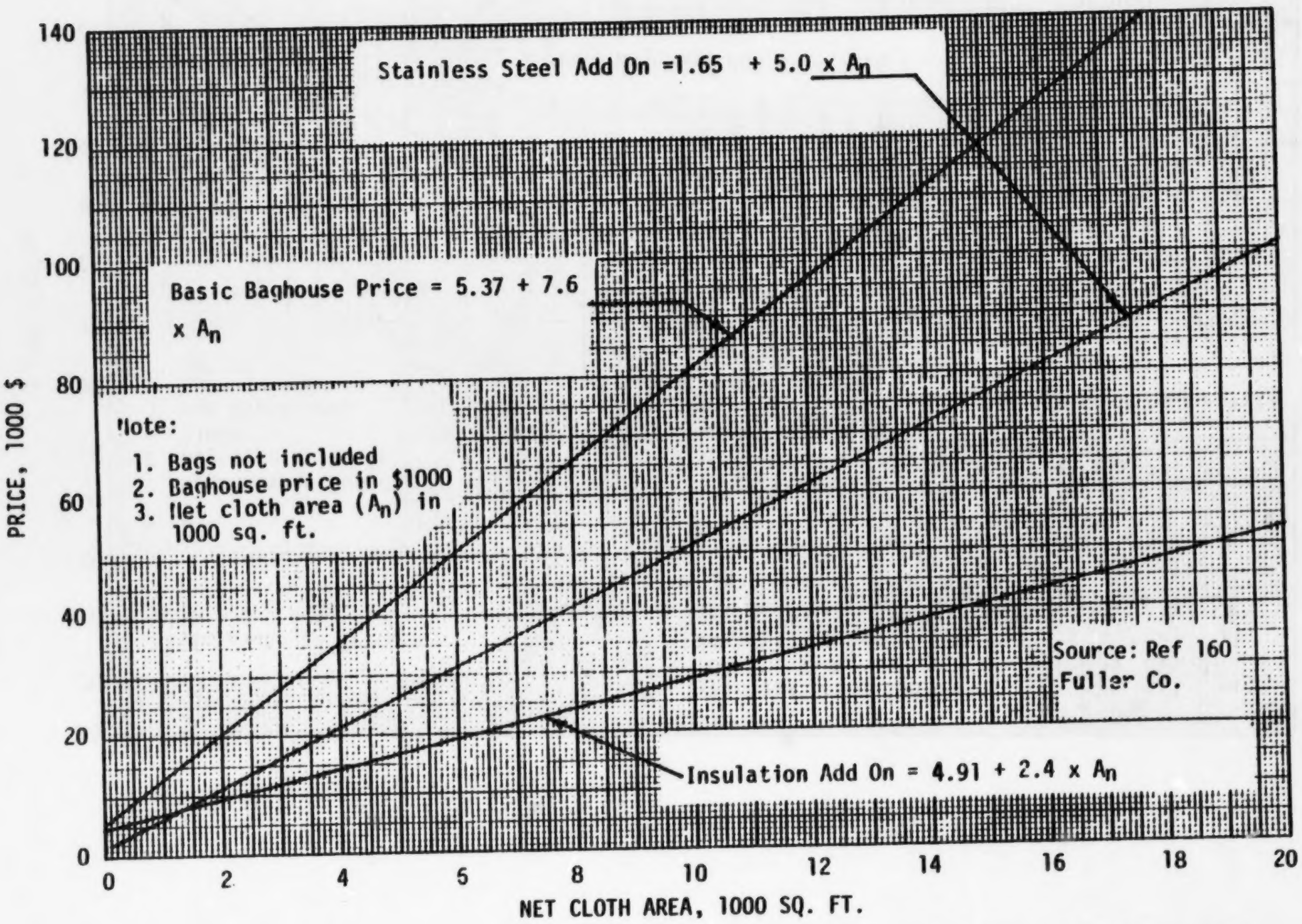


Note:

1. Bags not included
2. Baghouse price in $1000
3. Net cloth area (A_n) in 1000 sq. ft.

Source: Ref 160
Fuller Co.

Figure 5-10 INTERMITTENT, PRESSURE, MECHANICAL SHAKER BAGHOUSE VS. NET CLOTH AREA



Note:
1. Bags not included
2. Baghouse price in $1000
3. Net cloth area (A_n) in 1000 sq. ft.

Source: Ref 160 Fuller Co.

Figure 5-11 CONTINUOUS, SUCTION OR PRESSURE, PULSE JET BAGHOUSE PRICES VS. NET CLOTH AREA

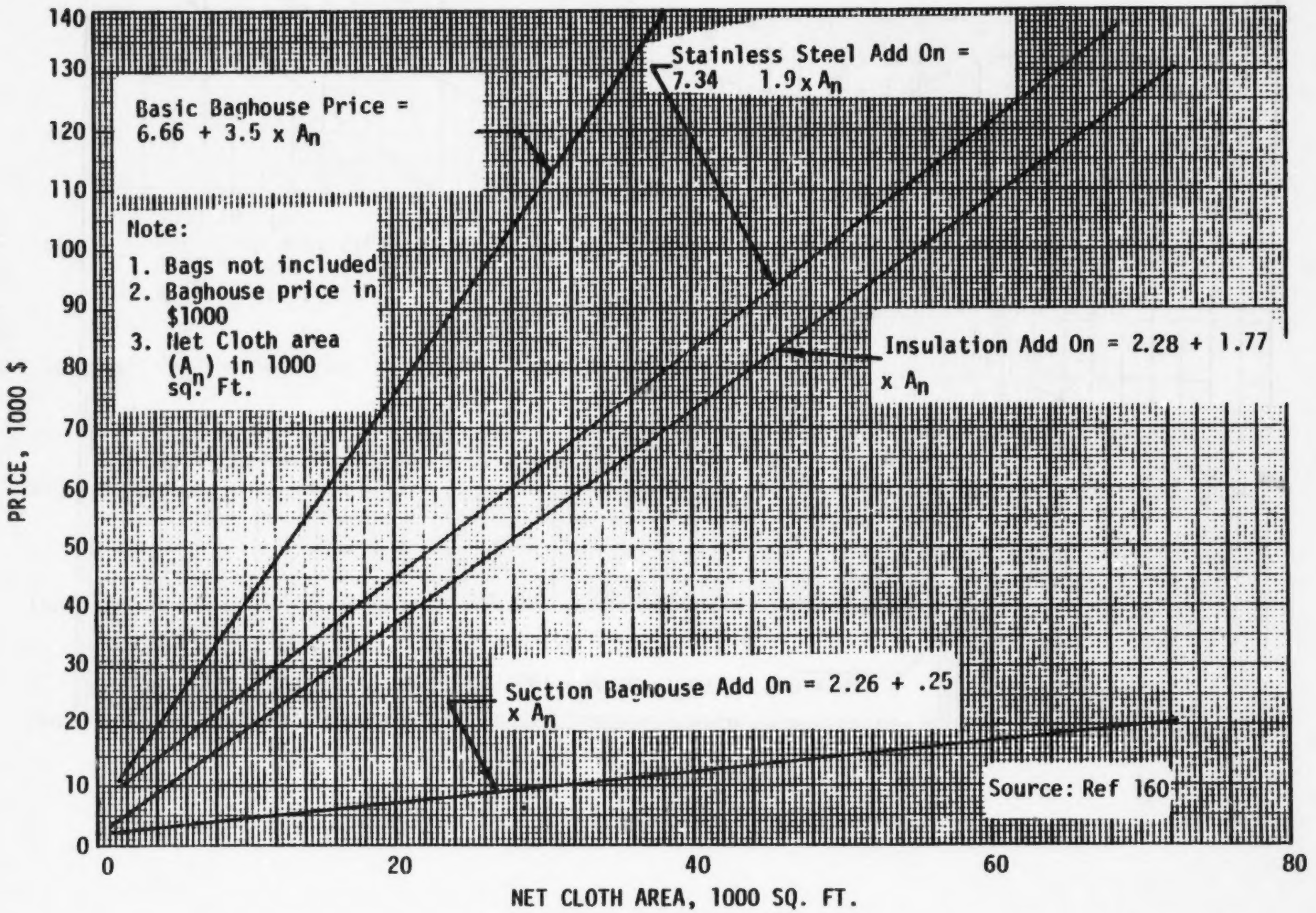


Figure 5-12 CONTINUOUS, PRESSURE, MECHANICAL SHAKER BAGHOUSE PRICES VS. NET CLOTH AREA

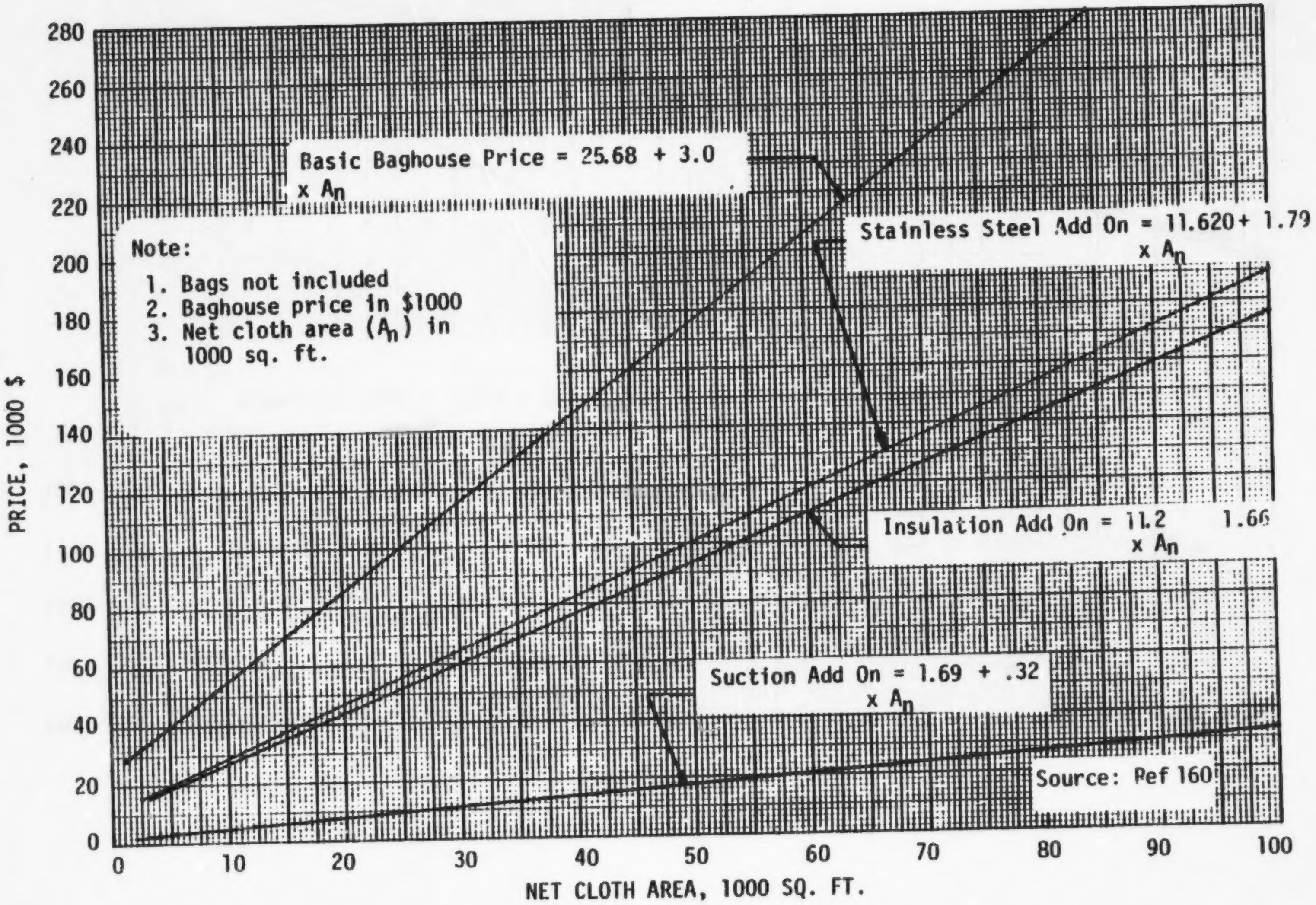
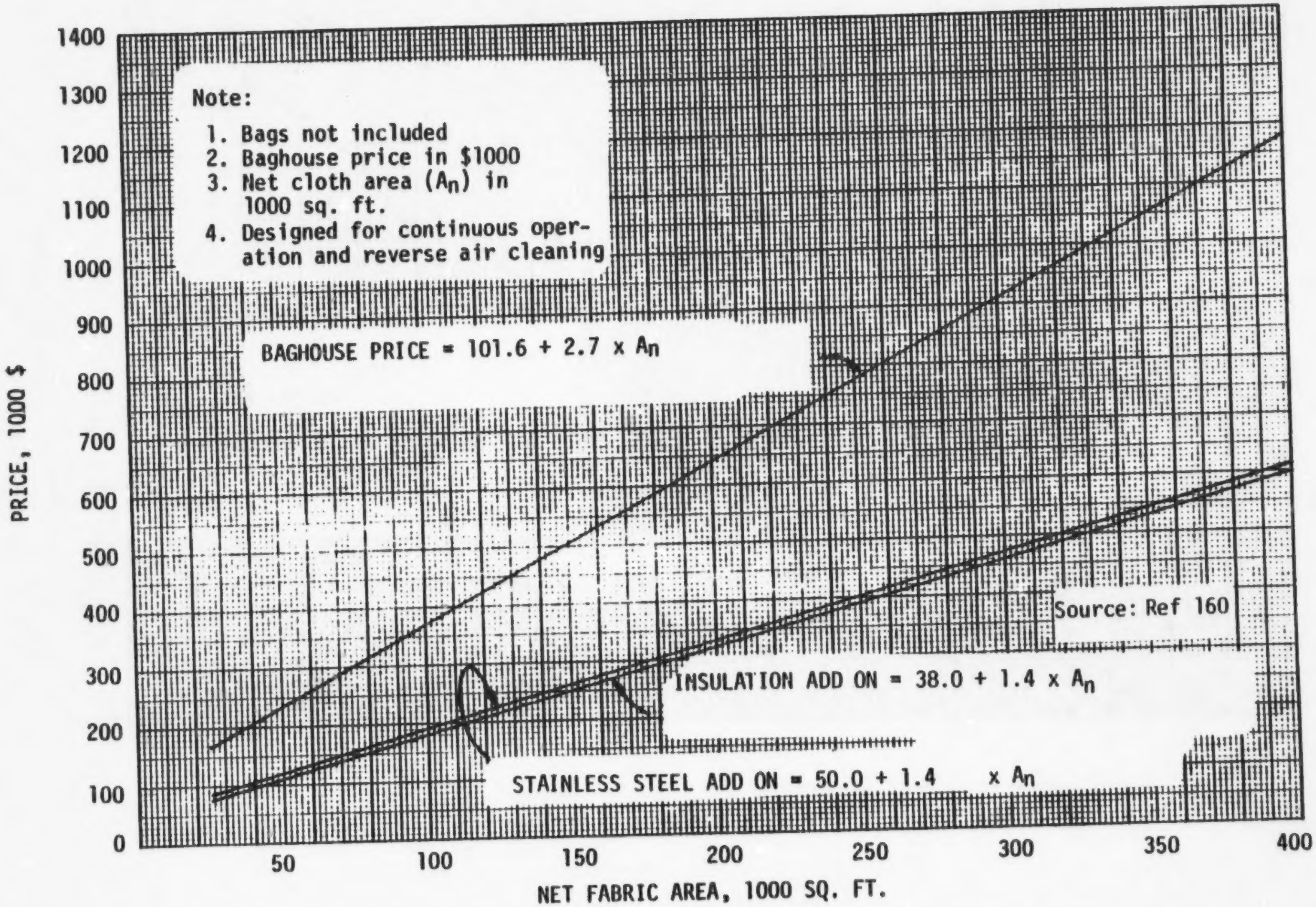


Figure 5-13 CONTINUOUS, PRESSURE, REVERSE AIR BAGHOUSE PRICES VS. NET CLOTH AREA



Note:

1. Bags not included
2. Baghouse price in $1000
3. Net cloth area (A_n) in 1000 sq. ft.
4. Designed for continuous operation and reverse air cleaning

Source: Ref 160

Figure 5-14 CUSTOM PRESSURE OR SUCTION BAGHOUSE PRICES VS. NET CLOTH AREA

design, the total price without bags would be:

Baghouse	$176,000
SS	100,000
Insulation	94,000
Suction	18,000
Total	$388,000

The prices for bags may be determined from Tables 5.1 and 5.2. From Table 5.2 obtain factor to calculate gross cloth area (at 50,000 ft^2 the factor is 1.11) and from Table 5.1 obtain the price per square foot for the appropriate cloth and baghouse type. The price of glass bags for the example is thus:

$$50{,}000\ ft^2 \times 1.11 \times \$.45/ft^2 = \$24{,}975$$

Baghouse prices are flange-to-flange, including basic baghouse without bags, 10 foot support clearance, and inlet and exhaust manifolds. Pressure baghouses are designed for 12" W.G. and suction baghouses are designed for 20" W.G. Custom baghouse prices are more a function of specific requirements, than of pressure or suction construction so prices do not differentiate between pressure or suction. Custom baghouses are designed for continuous operation and normally use reverse air cleaning. All baghouses except custom baghouses are assumed to be factory assembled.

5.4 Thermal and Catalytic Incinerator Systems

Gas cleaning by thermal or catalytic incineration is well suited for processes that emit combustible gases, vapors, aerosols, and particulates. These systems are used extensively in removing odors and in reducing the opacity of visible plumes from ovens, driers, stills, cookers and refuse incinerators. The method consists of ducting the exhaust process gases to a combustion chamber which employs either a catalyst bed or direct-fired burners to combust the contaminant gases to carbon dioxide and water vapor. Direct-fired gas burners are more commonly used because of their simplicity and reliability. However,

Table 5.1 BAG PRICES ($/SQ.FT.) Ref. 160

CLASS	TYPE	DACRON	ORLON	NYLON	NOMEX	GLASS	POLYPROPYLENE	COTTON
Standard	Mechanical shaker, < 20000ft^2	.40	.65	.75	1.15	.50	.65	.45
	Mechanical shaker, > 20000ft^2	.35	.50	.70	1.05	.45	.55	.40
	Pulse jet*	.60	.95		1.30		.70	
	Reverse air	.35	.60	.70	1.05	.45	.55	.40
Custom	Mechanical shaker	.25	.35	.45	.65	.30	.35	.40
	Reverse air	.25	.35	.45	.65	.30	.35	.40

* For heavy felt, multiply price by 1.5

Table 5.2 APPROXIMATE GUIDE TO ESTIMATE GROSS CLOTH AREA

NET CLOTH AREA (Sq.ft.)	GROSS CLOTH AREA (Sq.ft.)
1 - 4000	Multiply by 2
4001 - 12000	" 1.5
12001 - 24000	" 1.25
24001 - 36000	" 1.17
36001 - 48000	" 1.125
48001 - 60000	" 1.11
60001 - 72000	" 1.10
72001 - 84000	" 1.09
84001 - 96000	" 1.08
96001 - 108000	" 1.07
108001 - 132000	" 1.06
132001 - 180000	" 1.05
180001 ON UP	" 1.04

catalytic units produce combustion at lower temperatures which can result in lower fuel costs. In direct-fired thermal incinerators (afterburners), the contaminated gas stream is delivered to the refractory lined burner area by the process exhaust system or by a self contained blower. The introduction of the gas stream at the burners insures turbulence and complete mixing with the combustion products at the highest temperatures possible. The gas stream and combustion products then enter the retention chamber at lower velocities to increase residence time and ensure complete oxidation of the combustibles. To reduce fuel costs, recuperative heat exchangers can be used downstream of the retention chamber to recover heat from the exhaust gases and preheat the inlet contaminated gas stream. A second method of recovering heat from the afterburner exhaust is to recycle a portion of this gas to the inlet gas stream. The efficiency of direct-fired afterburners depends on the type and concentration of contaminants in the inlet gases, the operating temperature, the mixing of gases in the afterburner, and the residence time. Heat exchangers, when added, increase the thermal efficiency and reduce fuel costs at the expense of higher initial costs. Secondary heat recovery may also be used to recover heat from the exhaust stream for use in the basic process or for other purposes such as ovens, dryers, vaporizers, etc.

Direct-fired thermal incinerators can be provided as packaged units for small volume applications which include the basic chamber, fan, and controls. Larger units are usually custom designed or are modifications of standard components integrated into a complete unit. The amount of controls and instrumentation required for these systems will depend on the characteristics of the process gas stream. Steady state processes require the least amount of controls, whereas fluctuating gas streams would require modulating controllers for the burners, recycled gas, etc.. Most units only require basic controls such as safety pilots and flame failure shut-offs, high temperature shut-offs (fan failure), temperature monitors and recorders. The fans used for these units are usually axial flow or low pressure centrifugal type since pressure drops for the incinerator alone are low (less than 2 inches W.G.). If a heat exchanger is included, the pressure drop may increase up to 6 inches W.G. depending on the configuration of the heat exchanger and the number of passes.

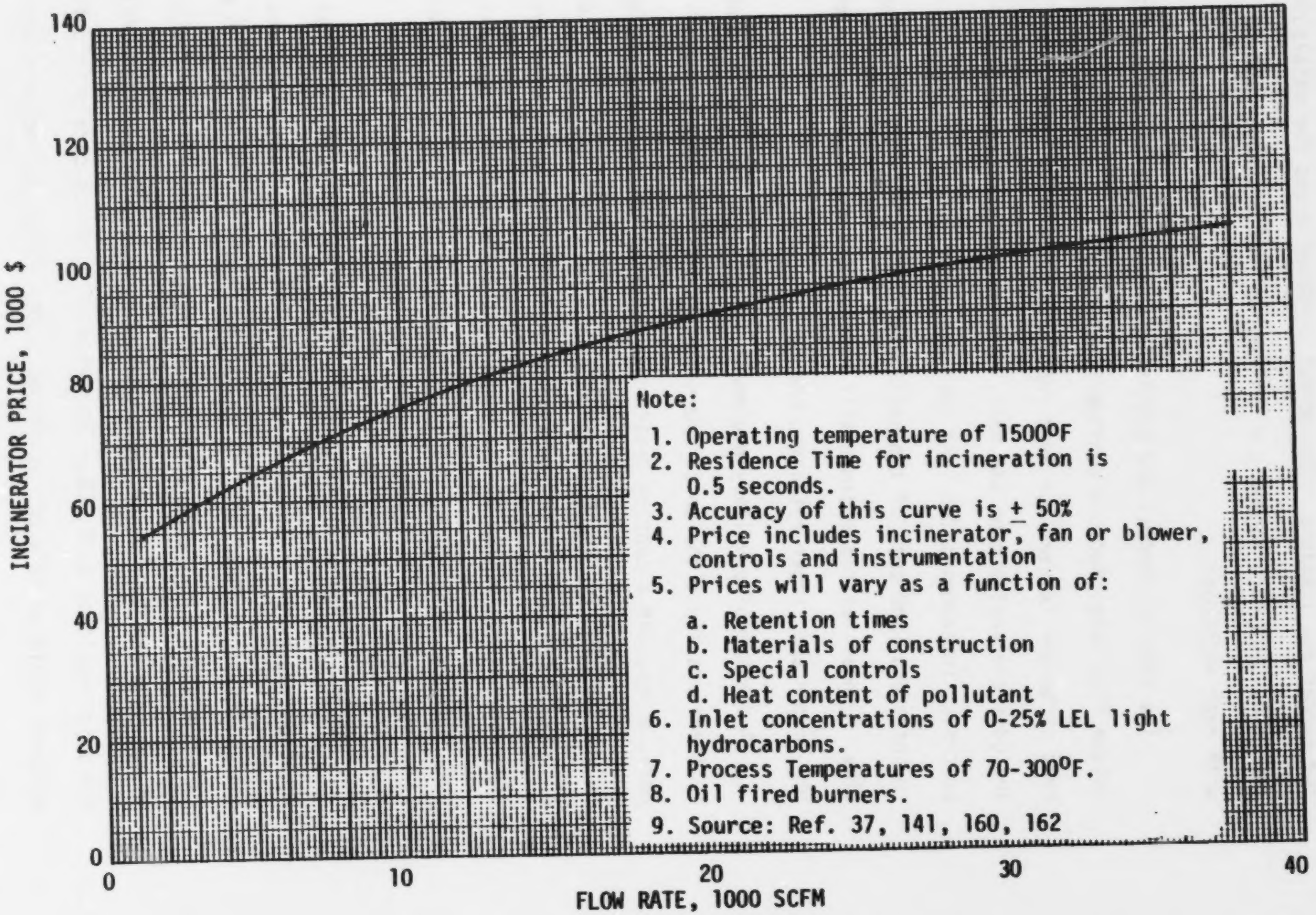
An alternative to the direct-fired thermal incinerator is the catalytic incinerator which utilizes a catalyst bed to oxidize the contaminants to carbon dioxide and water vapor. This reaction takes place at lower temperatures (650-1200°F) than the direct-fired incinerator (850-1800°F) and usually results in lower fuel costs. One of the limitations of the catalytic incinerator is its susceptibility to fouling and degradation by particulates or metal poisons such as zinc, lead, tin, etc. For this reason, the gas streams containing organic vapors or solvents are better suited for catalytic combustion while those containing fumes and smokes should be controlled by the direct-fired incinerator.

The catalytic incinerator consists of the catalyst bed, preheat burners, ductwork, fan, and controls. The preheat burners are required to raise the temperature of the inlet gas stream to a level compatible with the oxidation reaction temperature of the catalyst. To conserve on fuel costs, the preheat burners can be regulated by controllers monitoring the exit gas temperature of the catalyst bed. As the bed temperature increases from heat transferred by the exothermic reaction, the amount of heat supplied by the preheat burners can be reduced accordingly. This can result in a savings of approximately 40-60 percent in fuel costs as compared to the direct-fired incinerator. The catalytic incinerator, however, has a higher maintenance cost than the direct-fired incinerator due to the necessity of periodically cleaning the catalyst bed and the eventual replacement of the bed. Catalytic incinerators are available in packaged units for small volume applications and custom units for larger applications. The normal pressure drops for catalytic incinerators can be as high as 6 inches W.G. without a heat exchanger and 10 inches W.G. with heat exchanger.

The cost of thermal and catalytic incinerators is based on the inlet gas volume flow rate, factors considering package or custom design, and whether a heat exchanger is used for heat recovery. The basic cost of the incinerators includes the incinerator and base, fan, motor, starter, integral ductwork, controls, instrumentation, and heat exchanger (where applicable). For thermal incinerators, the cost of the units also varies with the designed residence time. Longer residence times will necessitate higher cost equipment due to the longer and larger retention chambers.

A minimum of auxiliary equipment is required for thermal and catalytic incinerators since the units are normally self-contained. Usually some ductwork, a fan, and a capture device are required to transport the process gas stream from the source to the control device if the distance is appreciable. A separate fan however is supplied with the incinerator to ensure proper distribution and mixing of the gases in the incinerator. An exhaust stack is also required to disperse the exhaust gases above the level of the surrounding buildings.

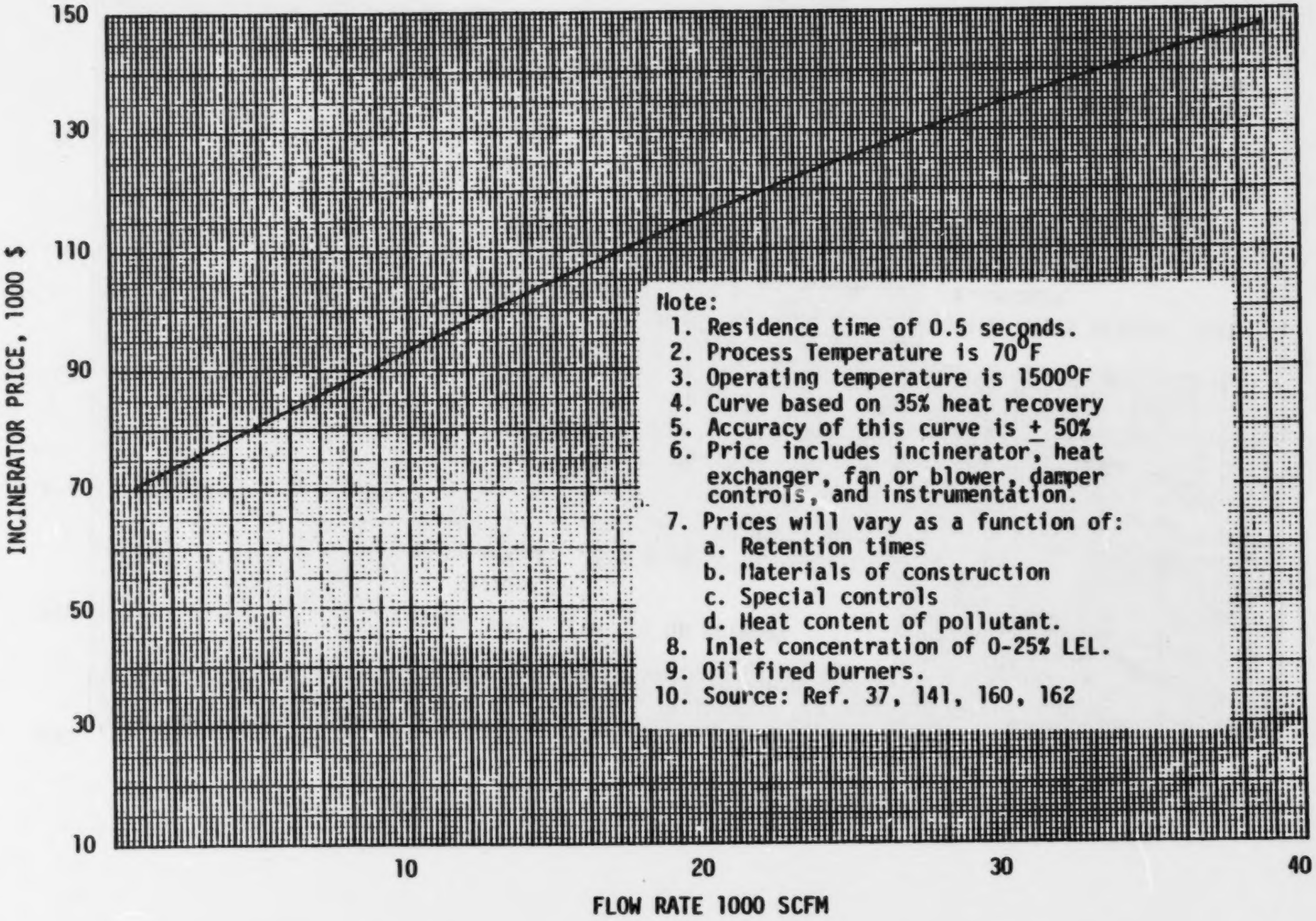
Prices for thermal incinerators including refractory linings, are contained in Figures 5-15 and 5-16. Catalytic incinerator prices are found in Figure 5-17. Residence times for thermal incinerators are based on 0.5 seconds. The price of a thermal incinerator without heat exchanger for a gas volume of 30,000 SCFM and 0.5 second residence time is $99,000. With a heat exchanger, the price would be $135,000. The price of a custom catalytic unit with heat exchange would be $234,000 at 30,000 SCFM. Note, gas volumes are measured at standard conditions.



Note:

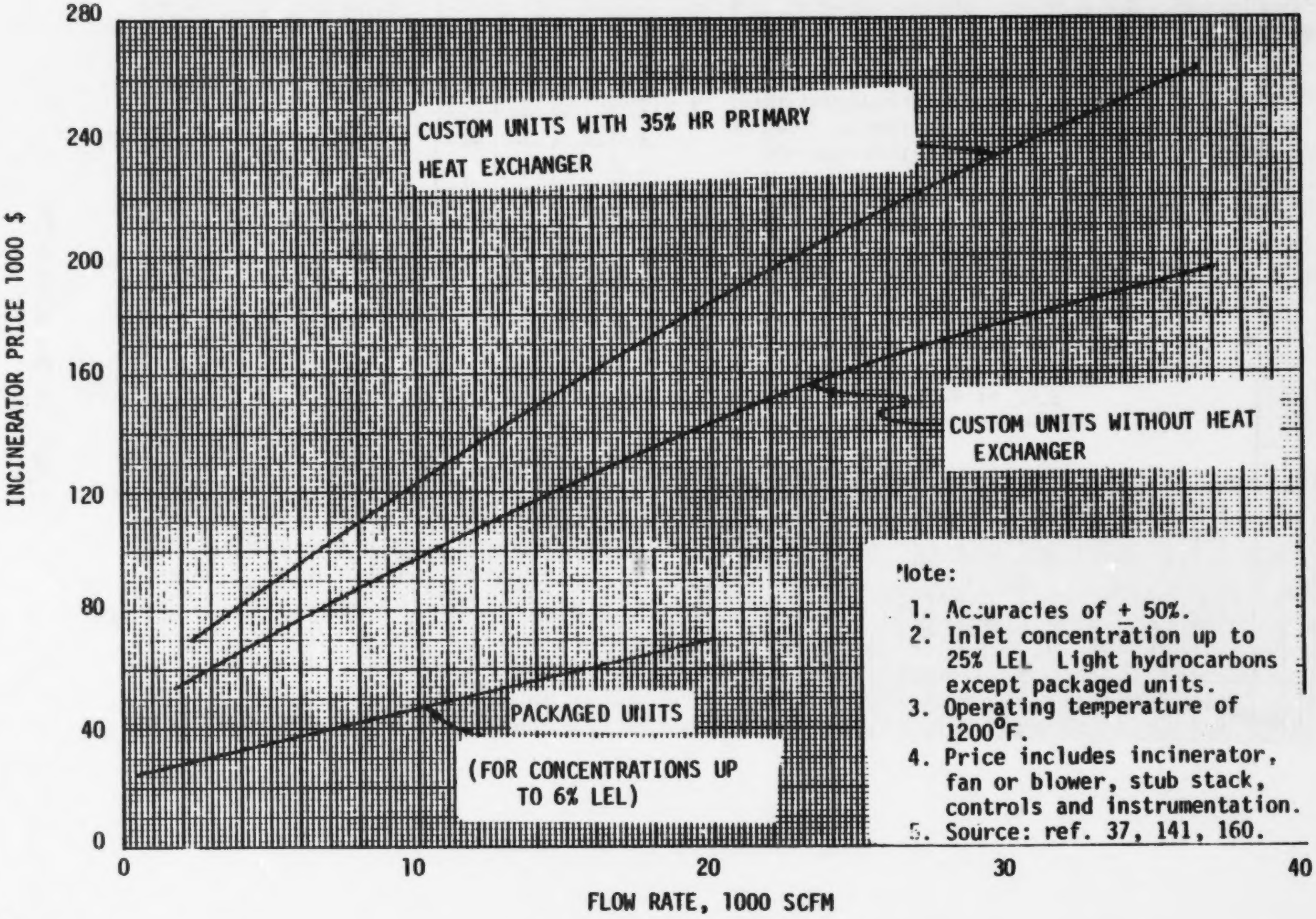
1. Operating temperature of 1500°F
2. Residence Time for incineration is 0.5 seconds.
3. Accuracy of this curve is ± 50%
4. Price includes incinerator, fan or blower, controls and instrumentation
5. Prices will vary as a function of:
   - a. Retention times
   - b. Materials of construction
   - c. Special controls
   - d. Heat content of pollutant
6. Inlet concentrations of 0-25% LEL light hydrocarbons.
7. Process Temperatures of 70-300°F.
8. Oil fired burners.
9. Source: Ref. 37, 141, 160, 162

Figure 5-15 PRICES FOR THERMAL INCINERATORS WITHOUT HEAT EXCHANGERS



Note:
1. Residence time of 0.5 seconds.
2. Process Temperature is 70°F
3. Operating temperature is 1500°F
4. Curve based on 35% heat recovery
5. Accuracy of this curve is ± 50%
6. Price includes incinerator, heat exchanger, fan or blower, damper controls, and instrumentation.
7. Prices will vary as a function of:
    a. Retention times
    b. Materials of construction
    c. Special controls
    d. Heat content of pollutant.
8. Inlet concentration of 0-25% LEL.
9. Oil fired burners.
10. Source: Ref. 37, 141, 160, 162

Figure 5-16 PRICES FOR THERMAL INCINERATORS WITH PRIMARY HEAT EXCHANGER



Note:

1. Accuracies of ± 50%.
2. Inlet concentration up to 25% LEL Light hydrocarbons except packaged units.
3. Operating temperature of 1200°F.
4. Price includes incinerator, fan or blower, stub stack, controls and instrumentation.
5. Source: ref. 37, 141, 160.

Figure 5-17 CATALYTIC INCINERATOR PRICES

Reference 37 should be consulted for design and cost details of incinerators having different residence times. A thorough discussion of the difference in costs of materials is also included. Longer residence time requires longer residence chambers and consequently higher costs. The type and temperature limits of the refractory linings will also affect the cost of the incinerator. For approximation purposes, a reduction in residence time from 0.5 seconds to 0.2 seconds will result in a cost reduction of 25 percent. Increasing the residence time to 1 second will increase the costs by approximately 25 percent. Secondary heat recovery may be added through the use of a waste heat boiler or a secondary heat exchanger. The cost of secondary heat recovery is difficult to estimate because of the variety of devices used for this purpose. If a secondary air-to-air heat exchanger is used downstream of an incinerator with primary heat recovery, the added costs can be estimated to be 25 percent of the incinerator/primary heat exchanger costs.[141]

The cost curves for thermal incinerators are based on an operating temperature of 1500°F. The cost of incinerators operating at other temperatures can be determined by adjusting the inlet gas flowrates to account for the temperature difference as follows.

$$\frac{\text{Flowrate (SCFM) at } t}{\text{Flowrate (SCFM) at } t_b} = \frac{t + 460}{t_b + 460}$$

where: t = new temperature, °F

t_b = baseline temperature, 1500°F

5.5 Adsorbers

Gas cleaning by adsorption is used primarily in the removal of organic liquids and vapors from process streams. The principles of adsorption and the affinity of certain adsorbents for specific compounds are quite complex.

The process can be described as the mechanical and chemical bonding of a substance on the surface of an adsorbent. The control system using this principle usually consists of at least two adsorbent beds with one bed on stream adsorbing while the second bed is regenerating. Regeneration is usually accomplished by heating the adsorbent to a high temperature to drive off the adsorbed compounds. Continuous adsorbers have also been devised where adsorption and regeneration take place in different positions of the same bed, which is progressively displaced through the vessel. Some problems that exist in adsorption systems are the result of solids in the process gas stream. Particulate matter in the gas stream can be detrimental to adsorber beds by blinding the adsorbent; therefore, efficient filters must be provided at the inlet to the beds. Corrosion is also a factor in the maintenance of the beds and equipment, and is usually related to the method of bed regeneration. Activated carbon is the most widely used adsorbent in industry; however, other adsorbents such as silica gel, bauxite, and alumina are used for some specific processes. The regeneration of activated carbon adsorption beds is normally accomplished by passing steam through the bed in the opposite direction of the normal gas flow during adsorption. The flow rate, temperature, and pressure of the steam required for regeneration is dependent on the type and characteristics of the adsorbate and the quantity adsorbed. After regeneration, the beds are normally cooled by passing clean air through the carbon before being placed on stream. Fixed bed adsorbers usually consist of at least two beds; one adsorbing while the other is regenerating. If the time for regenerating and cooling is longer than the adsorption time, three beds may be used; one adsorbing, one regenerating, and one cooling. The operations involved with switching beds from the adsorption stage to the regeneration stage can be either manual or automatic. Automatic systems cost more due to the mechanisms and controls required. Carbon adsorbers are supplied as either packaged units for small volume applications or custom designed units for larger applications. The units, as supplied, consist of the adsorber beds, activated carbon, fans or blowers, controls, and the steam regenerator (excluding steam source).

The capital cost for a carbon adsorber is based on the gross weight of carbon required for the application. The amount of carbon is determined by the ventilation rate, the type and mass emission rate of the pollutant, the length of the adsorption and regeneration cycle, and the carbon adsorption capacity at operating conditions. The key design parameters that determine the size of the carbon adsorber are the face velocity and the bed depth. The desired face velocity is approximately 80 to 100 feet per minute for most commercial and industrial applications involving solvent recovery and the depth of the beds may vary from 6 inches to 30 inches. For air purification systems where the concentration of pollutants is in the order of 1 ppm or less, the desired face velocity is reduced to approximately 40 fpm with bed depths of 0.5 to 3 inches. For a given ventilation rate in acfm, the face velocity and bed depth determine the working bed volume and consequently the weight of carbon.

For design purposes, the working bed volume for a selected cycle time can be determined from the adsorption isotherm for the particular adsorbent and adsorbate. The adsorption isotherm is a plot of the adsorption capacity at constant temperature as a function of the vapor pressure or the relative partial pressure of the adsorbate in the gas stream. Normally, the adsorption capacity of an adsorbent increases with increased vapor pressure and decreases with increased temperature. Using the appropriate adsorption isotherm, the adsorption capacity in pounds adsorbed per pound of adsorbent can be obtained for the desired operating conditions. The adsorption capacity is then multiplied by a design factor of between 0.1 and 0.5 to determine a working capacity. From discussions with manufacturers, a design factor of 0.25 is adequate for preliminary sizing of most applications (Ref 151). The weight of carbon for each bed is then determined by multiplying the emission rate in pounds per hour by the adsorption time in hours and dividing by the working capacity in pounds adsorbed per pound of adsorbent. For example, assume that toluene vapors at 70°F are to be recovered from a source at a rate of 6.15 lb/min. and the inlet concentration to the adsorber is to be maintained at 25% of the lower explosive limit (LEL). The LEL for toluene in air is 1.29% or 3.07 lbs/1000 cu.ft.; hence, 25% of the LEL would be 0.32% or 0.768 lbs/1000 cu.ft.. The flow rate through the adsorber is determined by dividing the recovery rate (6.15 lbs/min) by the concentration (0.768×10^{-3} lbs/cu.ft.) to obtain a gas volume rate of 8000 cfm. The vapor pressure of the toluene in air at a total pressure of 760mm Hg is determined by multiplying the concentration (0.0032) by the operating pressure (760 mm Hg) to obtain a pressure of 2.4 mm Hg. Using the adsorption isotherm in Figure 5-18, the adsorption capacity in percent by weight at this vapor pressure is 35% or 0.35 lbs of toluene per lb. of carbon. Note that the adsorption isotherm is for operating temperatures of 21°C (70°F) and operating pressures of 760 mm Hg with a carbon adsorbent having a density of 27 lbs/cu.ft.. A working capacity of 8.75% is obtained by multiplying the adsorption capacity from Figure 5-18 by a design factor of 0.25. If the adsorption period is one hour per bed, then 369 lbs of toluene (6.15 lbs/min x 60 min/hr) will be recovered per bed. The carbon requirements per bed will be 369 lbs/hr divided by 0.0875 lbs toluene/lb carbon or approximately 4200 lbs per bed.

Adsorption isotherms for other hydrocarbons are available from handbooks and manufacturers literature. These isotherms are developed for particular

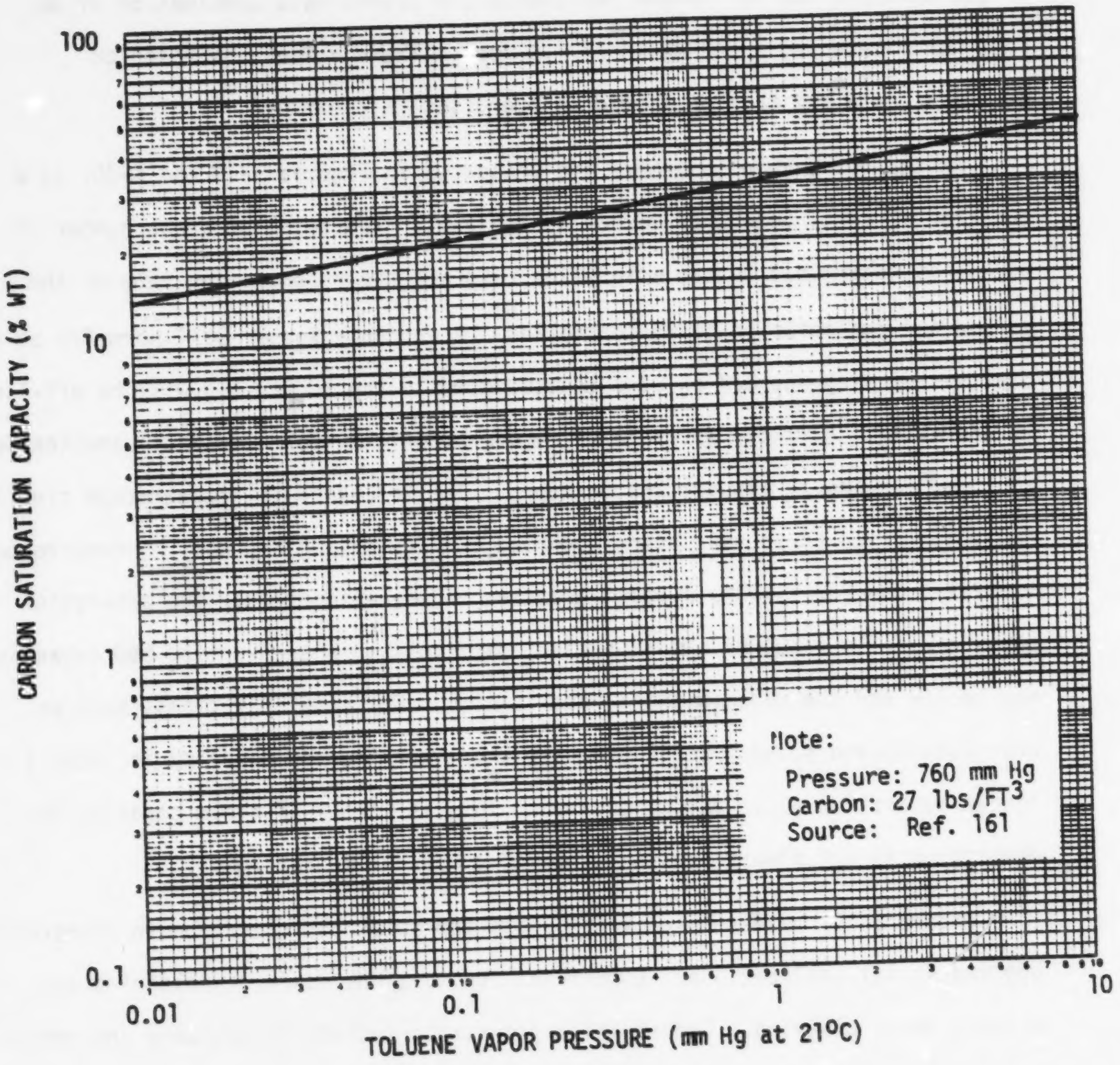


Figure 5-18 ADSORPTION ISOTHERM FOR TOLUENE

adsorbents operating at certain pressures and temperatures. Experimental work has also been done by carbon adsorber manufacturers and others to determine working bed capacities for various hydrocarbon emissions at a temperature of 100°F and a flow rate of 200 acfm per 100 lbs carbon (see Table 2.3). The value of 200 acfm per 100 lb. carbon represents the approximate combination of 80 feet per minute and a bed depth of 1.5 feet. These values are based on empirical data and caution should be exercised in their use.

Prices for carbon adsorbers are presented in Figures 5-19 and 5-20, as a function of total pounds of carbon in the unit. The total or gross number of pounds is determined by the adsorption rate and the regeneration rate of the carbon for the emission being controlled. A carbon adsorber will normally be a dual system with one bed on-line adsorbing while the second bed will be off-line regenerating. A likely estimate of regeneration time for almost all applications would be between 30 minutes and an hour. The variation in regeneration time is due to the type of solvent being desorbed and any drying and cooling requirements. Normally, one hour is the longest expected regeneration time. The adsorption phase generally requires one hour also; particularly where working bed capacity may be low and the mass emission rate is high. For some operations, such as dry-cleaning and solvent metal cleaning where working bed capacity is high, a longer adsorption phase may be desired. This is likely if steam capacity for desorption is not always available during a typical operating day.

Figure 5-19 represents packaged units for automatic operation in commercial and industrial applications. Commercial applications cover dry-cleaning and solvent metal cleaning. Industrial applications include lithography and petrochemical processing. Industrial requirements would increase costs 30 percent over commercial requirements. Industrial requirements would include heavier

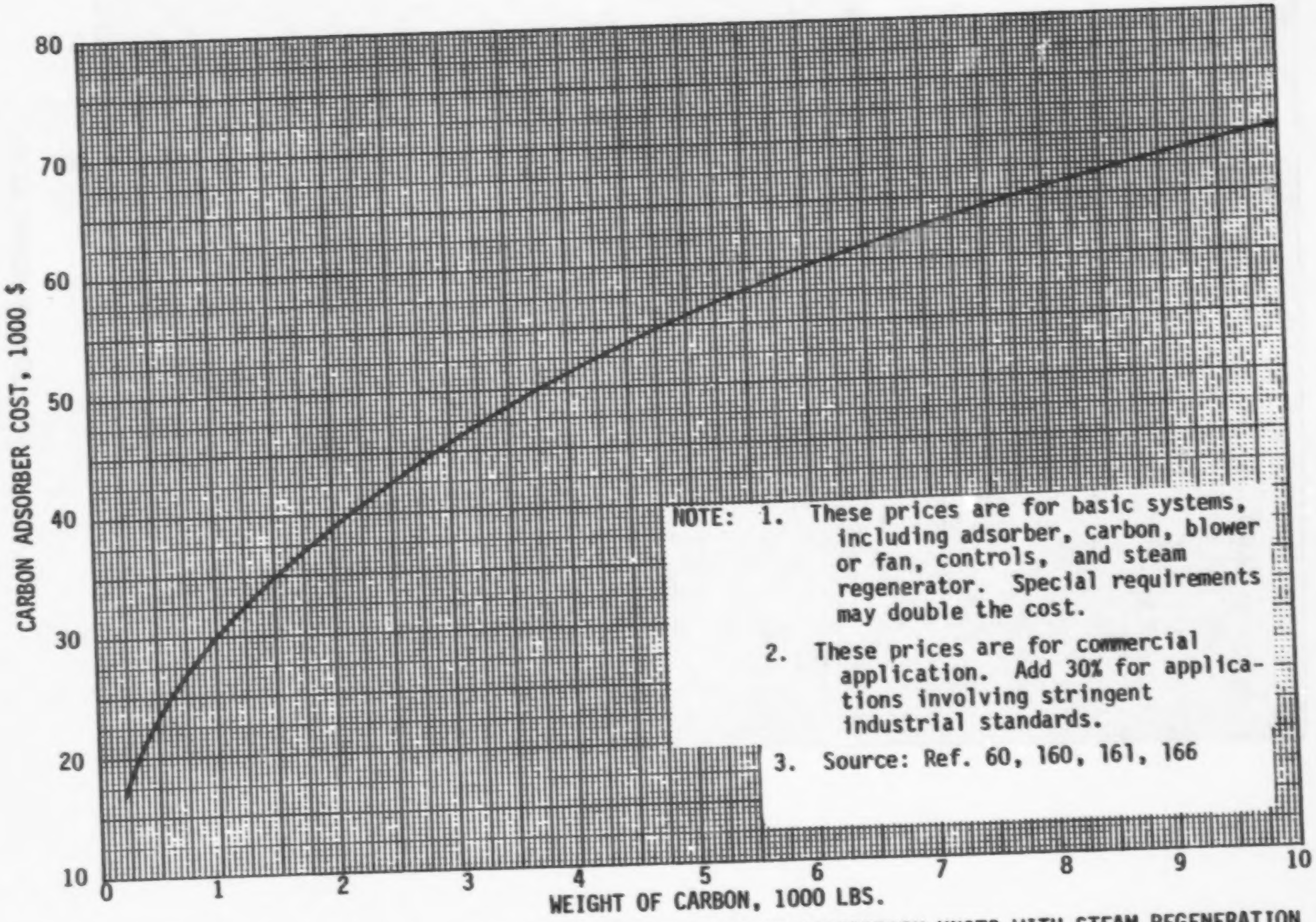
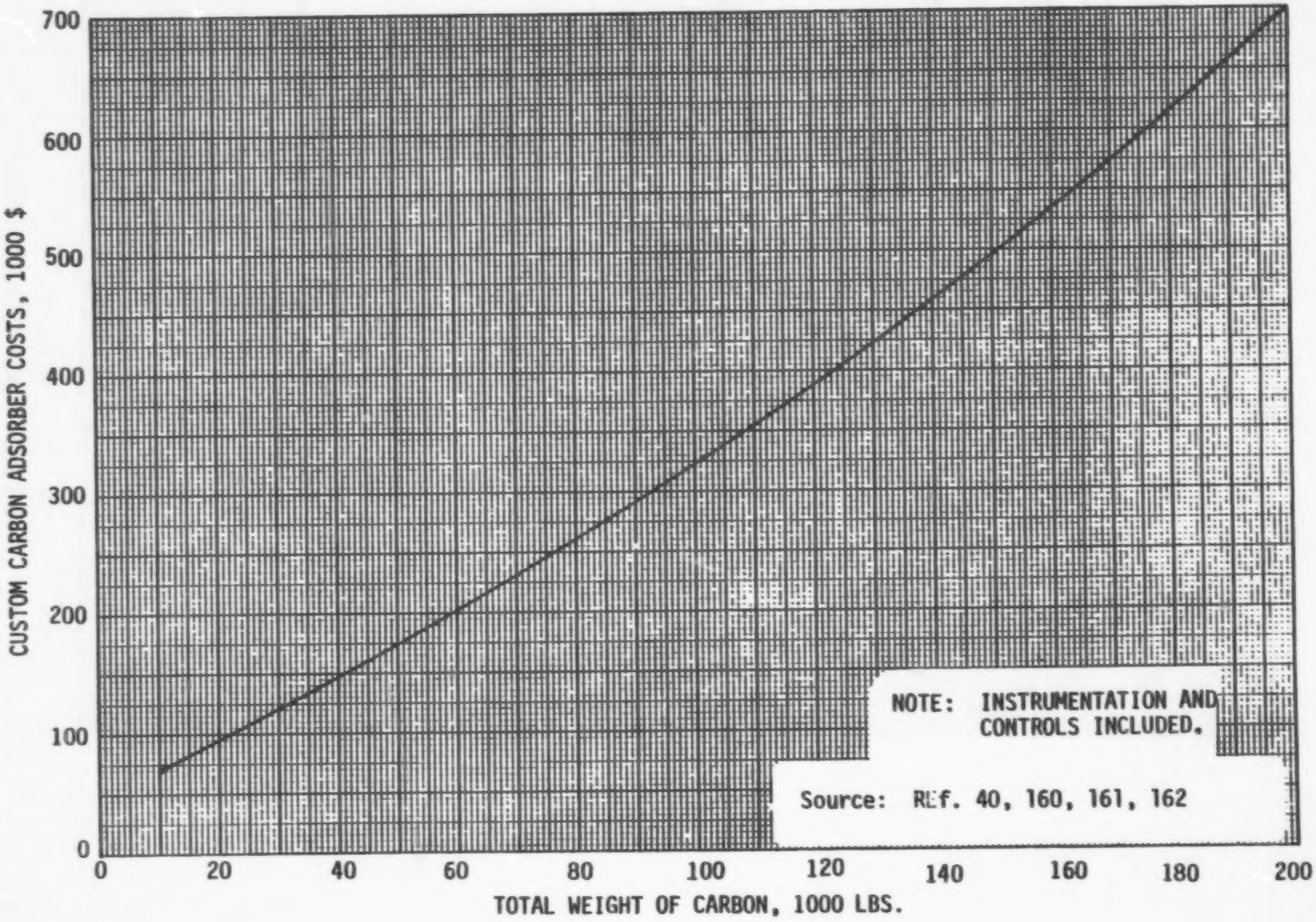


Figure 5-19 PRICES FOR PACKAGED STATIONARY BED CARBON ADSORPTION UNITS WITH STEAM REGENERATION

NOTE:
1. These prices are for basic systems, including adsorber, carbon, blower or fan, controls, and steam regenerator. Special requirements may double the cost.
2. These prices are for commercial application. Add 30% for applications involving stringent industrial standards.
3. Source: Ref. 60, 160, 161, 166



NOTE: INSTRUMENTATION AND CONTROLS INCLUDED.

Source: REf. 40, 160, 161, 162

Figure 5-20 PRICES FOR CUSTOM CARBON ADSORPTION UNITS

materials for high steam or vacuum pressure designs and more elaborate controls to assure safety against explosions and prevent hydrocarbon breakthrough. Figure 5-20 presents custom units, mostly for industrial applications where the gas flow rate exceeds 10,000 acfm. Table 5.3 is provided to estimate annualized control cost requirements for steam, cooling water, maintenance, electricity, and carbon replacement. These values and assumptions represent the composite of information provided by EPA contractual reports and in-house files. To use the values in Table 5.3 the required inputs are the pollutant emission rate, recovery efficiency, annual operating hours, exhaust gas rate, and the purchase price. The carbon weight used to determine the purchase cost can also be used to estimate the carbon replacement cost.

In Table 5.3, the steam consumption is based on the energy necessary to heat the bed and vessel from the operating temperature (100°F) to the solvent boiling temperature plus the energy required to evaporate the solvent from the bed. The heat of evaporation is directly proportional to the quanity of solvent present, however, the sensible heat added to the bed and vessel depends on the amount of carbon and the design of the bed. Some sources have related the steam usage to the quanity of carbon (0.3 lbs steam per lb carbon, Ref. 161), however, for study estimates, a value of 4 lbs steam per lb. solvent desorbed is reasonably accurate and acceptable. The cooling water requirement varies directly with the steam consumption rate in that it represents the heat removed in condensing and subsequent cooling of low pressure saturated steam. The electrical requirement is based on a pressure drop of 20 inches W.G. using a bed depth of 1.5 feet of 8-14 mesh carbon. The pressure drop through a carbon bed is a function of the carbon granule size, the size distribution, the packing of the bed and flow velocity. Given a specific carbon bed, the pressure drop through the bed will be proportional to the square of the superficial face velocity.

TABLE 5.3 TECHNICAL ASSUMPTIONS FOR ESTIMATION OF DIRECT OPERATING COSTS

Item	Assumption	Reference
Steam Consumption	4 lb per lb. pollutant recovered	MSA, DOW, STAUFFER, VIC
Cooling Water	12 gal per 100 lbs. steam	SHAW
Electricity	5 HP per 1000 ACFM	STAUFFER, MSA
Maintenance	5% of equipment purchase cost	Compromise between DOW and MSA
Carbon Replacement	Replace original carbon every five years	STAUFFER, MSA

MSA - "Hydrocarbon Pollutant Systems Study" by MSA Research Corp., EPA Contract EHSD 71-72, January, 1973.

DOW - "Study to Support New Source Performance Standards for Solvent Metal Cleaning Operations", EPA Contract 68-02-1329, Dow Chemical Co., June, 1976.

STAUFFER - Private communication from J. J. Harte, Stauffer Chemical Co. to Richard Schippers, EPA, April 11, 1977 on subject of carbon adsorber costs for control of ketones and toluene.

VIC - Private communication from J. W. Barber, Vic Manufacturing Co., to F. L. Bunyard, EPA, June 3, 1977.

SHAW - "Carbon Adsorption/Emission Control Benefits and Limitations", paper presented at Surface Coatings Industry symposium, April 26, 1979.

Since many adsorption applications involve recovery of a re-useable solvent, a by-product credit should be included in determining the annualized costs of control. This credit can have a substantial effect on the amortization rate of the capital costs of the equipment. For instance, in the previous example of an adsorber recovering toluene at a rate of 369 lbs per hour, the control device cost based on a unit having two beds (8400 lbs carbon total) is $66,500 (see Figure 5-19). The addition of taxes and freight at 8 percent from Table 3.3 results in a purchased equipment cost of approximately $72,000. The total installed cost for a typical installation (Table 3.3) is 1.61 x $72,000 or approximately $116,000. The total annualized cost can be determined based on the following assumptions: 1) 5800 hours annual operation, 2) 10-year equipment life, 3) 10% annual interest rate, 4) annual maintenance cost of 5 percent of capital costs, 5) a value of $0.10 per pound for the recovered product, and 6) operating labor requiring 360 man-hours per year at $7.87/man-hour. The cost basis is developed from Table 3.4 and the annualized cost breakdown is as follows:

1) Operating labor (360 m-h x $7.87/m-h)	$- 2,800
2) Maintenance (0.05 x $116,000)	$- 5,800
3) Carbon replacement at 5 year life $\left(\frac{8400\ \text{lb C}}{5\ \text{yr}} \times \$0.85/\text{lb C}\right)$	$- 1,400
4) Steam $\left(369\ \text{lb/hr} \times 5800\ \text{hr} \times 4\ \text{lb/lb} \times \frac{5.04\ \text{lb}}{1000\ \text{lb}}\right)$	$- 43,200
5) Electricity $\left(8000\ \text{cfm} \times \frac{5\ \text{hp}}{1000\ \text{cfm}} \times \frac{0.746\ \text{kwh}}{\text{hp}} \times 5800\ \text{hr} \times \$0.0432/\text{kwh}\right)$	$- 7,500

6) Cooling water -- $- 6,200

$$\left(\frac{12\text{ gpm}}{100\text{ lb steam}} \times \frac{1476\text{ lb steam}}{\text{hr}} \times \frac{60\text{ min}}{\text{hr}} \times 5800\text{ hr} \times \frac{\$0.10}{1000\text{ gal}}\right)$$

7) Capital charges @ 22% ---------------------------------- $- 25,500
(based on 10 yr. life, 10% interest & 5.725% for taxes, insurance, admin., etc.)

8) By-product credit --------------------------------------- ($- 214,000)

TOTAL $-121,600

The annualized costs for this example is a negative $121,600 indicating a decided cost advantage to solvent recovery for this application.

5.6 Absorbers

Gaseous pollutants in a process stream can be removed or reduced through absorption using a solvent having a high gas solubility to dissolve or chemically combine with the solute. The combined solvent and solute can then be further processed by stripping or desorbing to remove the solute and recover the solvent for reuse. In some cases the combined product may be returned to storage without separation as in the case of hydrocarbon recovery in oil or gasoline. Although absorption is used as a basic process in the chemical industry for the manufacture of acids and other chemical compounds, it is also used as an air pollution control device for the removal of gaseous contaminants such as sulfur dioxide and hydrogen sulfide from waste gas processes or the recovery of hydrocarbons from bulk storage and transfer operations.

The fundamental concept in the design of an absorber is the provision for good contact between the gas and the liquid. To achieve this, absorbers have been developed by the various manufacturers with specific proprietary design features. Each design, however, can be categorized by the type of construction and the method of contact employed. These are typically identified as packed tower, spray chamber, tray tower and venturi absorbers.

Packed towers and tray towers are the most common absorbers used today and the design considerations for each are amply covered in Reference 88. Packed towers consist of a vertical column filled with irregular-shaped packing, gas-liquid distributors, support plates for supporting the packing, liquid sprays, and entrance and exit ports for the liquid and gas streams. The gas and liquid flow through the column can be either concurrent or countercurrent, the latter being most often used. In the countercurrent tower, the gas enters the bottom of the column, passes through the packing material and exits at the top of the column. The liquid solvent is delivered to a manifold of sprays or other devices at the top of the column and is sprayed over the packing to wet the entire surface. The liquid solvent trickles down through the packing countercurrent to the gas flow rising through the column. To preclude channeling through the tower, particularly with long columns, distributors are located at intervals to redistribute the liquid over the cross-section of the column. These distributor plates have selective openings for both the gas and liquid. Support plates are also required at intervals to support the packing. These plates which may provide a dual function of both a support plate and a distributor plate, should have a larger open area than the column area with packing so that they do not substantially affect the overall pressure drop.

In the design of a packed tower, four basic parameters establish the size and operating characteristics of the unit. These include column diameter, pressure drop, number of transfer units and the height of the transfer unit.

To determine column diameter, the gas and liquid flow rates, gas and liquid densities, type of packing, and the liquid viscosity must be known or estimated. The superfical gas velocity and column diameter are determined from empirical graphs which estimate the pressure drop correlation and generalized flooding condition for various packings. The flood condition is a point at which increased gas flow will result in excessive pressure drop and liquid entrainment in the gas stream. Normally, design velocities for a packed tower are based on a certain percentage of the superficial gas velocity at the flooding condition. This percentage is based on the orientation and type of packing material.

The performance of the tower is predicted from experimental data in two forms: 1) the required number and height of transfer units, and 2) the gas and liquid film mass transfer coefficients. The use of either system is a matter of choice and usually depends on the units in which the operational and equilibrium data are presented. A thorough description of the development of the design criteria for a packed tower absorber using the transfer unit system is contained in Reference 88, "Air Pollution Control Manual" AP-40 and therefore that system of units will be used in this discussion. The transfer unit concept offers the advantage of the characteristics of the packed tower being expressed as a number of units with a corresponding height in feet. The number of transfer units is related to the efficiency of the absorption process itself, while the height of the units is concerned with the geometric and flow characteristics.

Using the transfer unit method of design, the column height can be determined from:

$$\text{column height} = H_{og} \times N_{og} + h_e$$

where: H_{og} = height of transfer unit

N_{og} = number of transfer units

h_e = added height for vapor/liquid separation, cleaning, etc.

The value, h_e, depends on the specific application, although it normally becomes less significant as H_{og} and N_{og} increase. The height of the transfer unit, H_{og}, can be determined from:

$$H_{og} = \frac{\alpha G^{\beta}}{L^{\gamma}} \left(\frac{\mu_g}{\rho_G D_G} \right)^{0.5} \qquad \text{(Ref. 88)}$$

where: α, β, γ are packing constants (see Ref. 88)

G = superficial gas mass flow rate through column (lb/hr-ft^2)

L = superficial liquid flow rate through column (lb/hr-ft^2)

μ_G = gas viscosity (lb/hr-ft)

ρ_G = gas density (lb/ft^3)

D_G = gas diffusivity (ft^2/hr)

Although the above equation (obtained from Ref. 88) neglects the effect of the liquid film resistance, it is sufficiently accurate for study estimate designs.

The number of transfer units, N_{og}, can be approximated by the following:

$$N_{og} = \frac{\ln \left[\left(1 - \frac{mG_m}{L_m}\right) \left(\frac{Y_1 - mX_2}{Y_2 - mX_2} \right) + \frac{mG_m}{L_m} \right]}{1 - \left(\frac{mG_m}{L_m} \right)}$$

where m = slope of the solute/solvent equilibrium curve

G_m = superficial molar gas flow rate (lb-mole/hr-ft^2)

L_m = superficial molar liquid flow rate (lb-mole/hr-ft^2)

Y_1 Y_2 = mole fraction of solute in gas stream at concentrated and dilute ends of countercurrent tower, respectively

X_2 = mole fraction of solute in liquid stream at dilute end of tower.

This equation for N_{og} is based on the work of Colburn (Ref. Trans. AICHE, 35,216 (1939) and is duscussed further in Reference 164. It is only applicable to those systems where the equilibrium curve is linear or where the solute concentration is less than 3 percent by volume. This encompasses most air pollution control applications.

An example problem illustrating the method of determining tower diameter, height and type of packing, flow rates and pressure drop for a packed tower absorber is contained in Reference 88. This design process must be completed to establish the equipment cost criteria for this type of absorber.

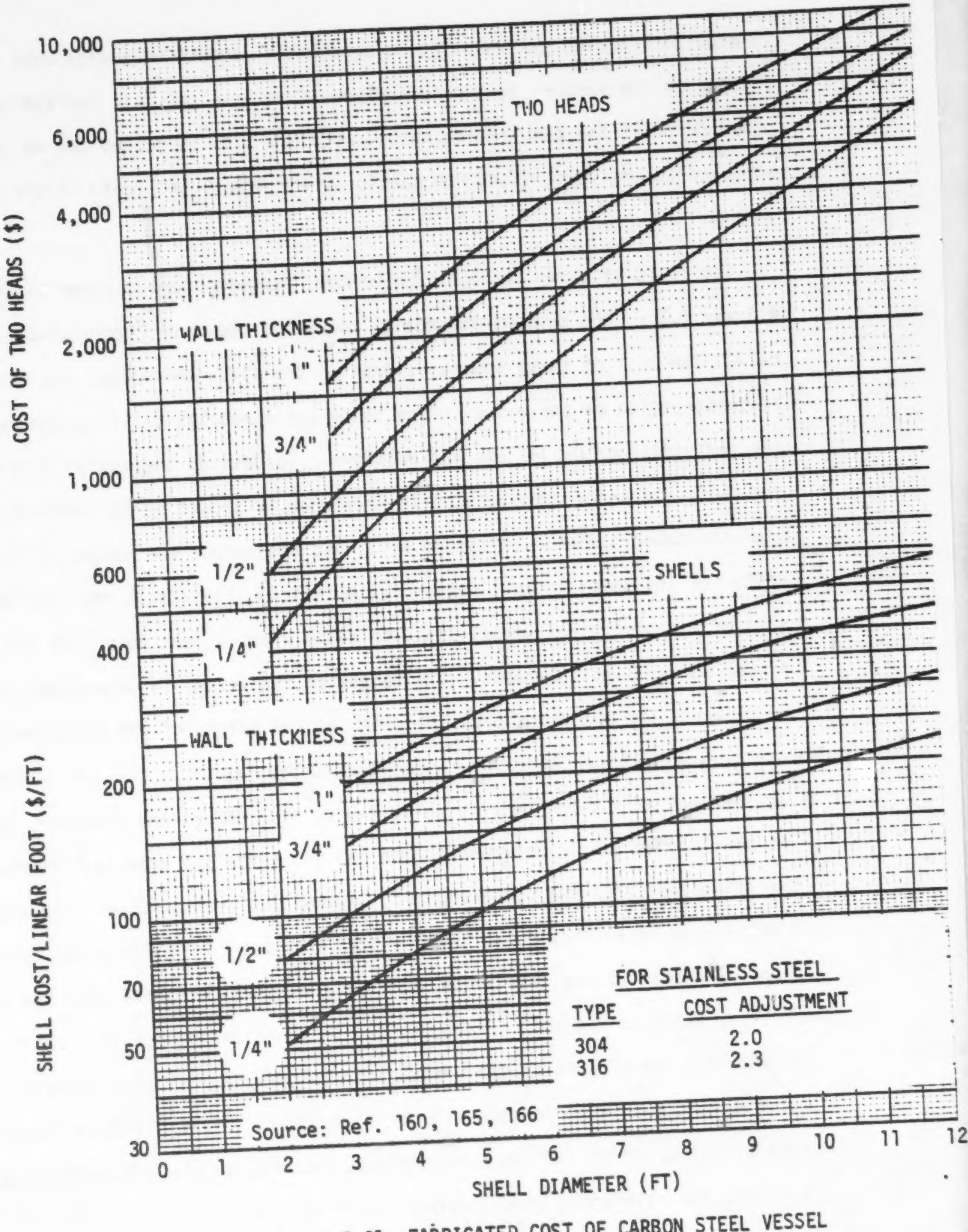
Tray towers are similar in many respects to packed towers. Instead of a gas-liquid interface on the surface of the packing, the gas is bubbled through the liquid contained in a tray. Several trays are arranged in a vertical column and the liquid cascades downward from one tray to the next. The trays are usually designed to permit vertical gas flow through bubble caps or perforations while the liquid level in the trays is maintained by a weir. Overflow from each tray cascades to the next lower tray and is removed from a sump at the bottom of the tower. The gas flow enters the bottom of the tower and passes upward through the openings of each tray, through the liquid held in each tray, and finally exits at the top of the tower. Theoretically, as the gas passes through each tray, it is assumed that the gas mixes with liquid of uniform composition and is in perfect equilibrium with the liquid. Even if perfect equilibrium is assumed, the absorption efficiency would not necessarily be 100 percent. The absorption efficiency is limited by the solute concentration in the solvent and the gas stream, the temperature, and other variables. However, perfect equilibrium cannot be obtained on an actual plate and therefore it is necessary to introduce a performance factor, known as the plate efficiency, to express the relation between the actual and an ideal plate. A discussion of the development of the design criteria for tray towers is also included in References 88 and 164. For a given application, the tower diameter, type and number of trays, and operating characteristics are needed to develop equipment and operating costs.

A simpler type of absorber is the spray chamber which provides gas-liquid contact without the use of packing material or trays. These devices are also used to cool hot gas streams or add moisture to the gas (see section 4). Typically, a spray chamber consists of an empty vessel equipped with a series of nozzles which spray liquid over the cross-section of the chamber while the gas passes through the sprays. The size of the droplets depends on the type and size of nozzles and the pressure of the liquid supply. Nozzles can be selected to provide a nominal droplet size, however, in the spraying process, some drops agglomerate while other disintergrate into smaller droplets. The fine droplets have a tendency to be entrained and carried away in the gas stream while the large droplets traverse the gas stream and collect on the walls of the chamber. This combined with the short contact time reduces the efficiency of the absorption process as such. One advantage of spray chambers is that both particulate and gaseous contaminants can be removed from a gas stream. This is of particular importance with gases that also produce solid deposits when reacted with the liquid solvent. Another advantage of spray chambers is the possibility of cooling gas streams at high temperatures where the packing material in a packed tower might be affected by these high temperatures. Spray chambers are used primarily where the absorbed gases have a high solubility and only a few transfer units are required for the absorption process. To reduce the carry-over or entrainment of small droplets, the gas velocity in a spray chamber must be low. As a result, the diameter of the chamber, and hence the cost, become rather large as the design flow rate is increased. To compensate for this, cyclonic spray chambers have been developed where the gas enters the chamber through a tangential opening and the liquid is injected at the axis through a row of nozzles. The cyclonic action assists the separation of the liquid droplets from the gas and permits higher gas velocities. The cost of spray chambers is related to the type and thickness of construction materials used, such as stainless steel, rubber-lined steel, etc., and the configuration of the vessel in terms of diameter, height, and tangential or axial inlet.

Venturi absorbers are similar to spray chambers in that they too can be used for gaseous and particulate removal. As described in Section 5.2, the venturi scrubber/absorber achieves contact between the gas and the liquid in the throat of the venturi where the gas is accelerated to high velocities at the point where the liquid is injected. The shearing action of the high velocity gas on the liquid stream or droplets produces a fine mist and good dispersal. The relative velocity between the gas and liquid droplets insures good contact. However, the contact period is short and the number of transfer units that can be expected is similar to that obtained with a spray chamber. As a result of the high velocities in the venturi and the fine droplets generated, the carry-over or entrainment is considerable and therefore a mist eliminator is generally required downstream to remove this liquid from the gas stream.

To provide the high gas velocity, a substantial amount of energy must be dissipated in the venturi in the form of pressure loss and this represents high power costs at the fan. Maintenance costs are also increased due to the abrasion at the venturi and fan caused by the impact of liquid in the gas stream.

The costs of spray chambers and venturi scrubbers are covered in Sections 4.3 and 5.2. The cost of absorption towers is shown in Figures 5-21 through 5-24. The cost of these towers depends on the size, thickness, and materials of construction of the vessel since these units are basically custom designed for individual processes and applications. To develop the design parameters, the design sequence demonstrated in Reference 88 should be followed to determine the tower diameter, pressure drop, and the number and height of transfer units for the specific application. Figure 5-21 illustrates the fabricated cost of a carbon steel vessel shell in dollars per linear foot plus the cost of two semi-elliptical heads. The height of the vessel is determined by multiplying the number of transfer units by the height of the transfer units plus some additional height for vapor/liquid separation at the top of the tower and cleanout at the bottom (typically 2-3 ft plus 25% of the diameter, ref. 38). The shell thickness is determined from Table 5.4 for the expected internal operating pressures and temperatures. In many cases a corrosion allowance of 1/8-1/4 inch is also added to the minimum thickness for carbon steel construction. The cost of the fabricated vessel alone, therefore, includes the cost of the shell plus the cost of two heads. The fabricated cost of a skirt which is provided for support of the vessel and flange-type nozzles for shell penetrations must also be added to the vessel cost. Figure 5-22 reflects the cost of skirts which include a base plate, anchors, an 18-inch diameter access opening, two reinforced pipe openings and a vent hole. The thickness of the



FOR STAINLESS STEEL

TYPE	COST ADJUSTMENT
304	2.0
316	2.3

Source: Ref. 160, 165, 166

Figure 5-21 FABRICATED COST OF CARBON STEEL VESSEL

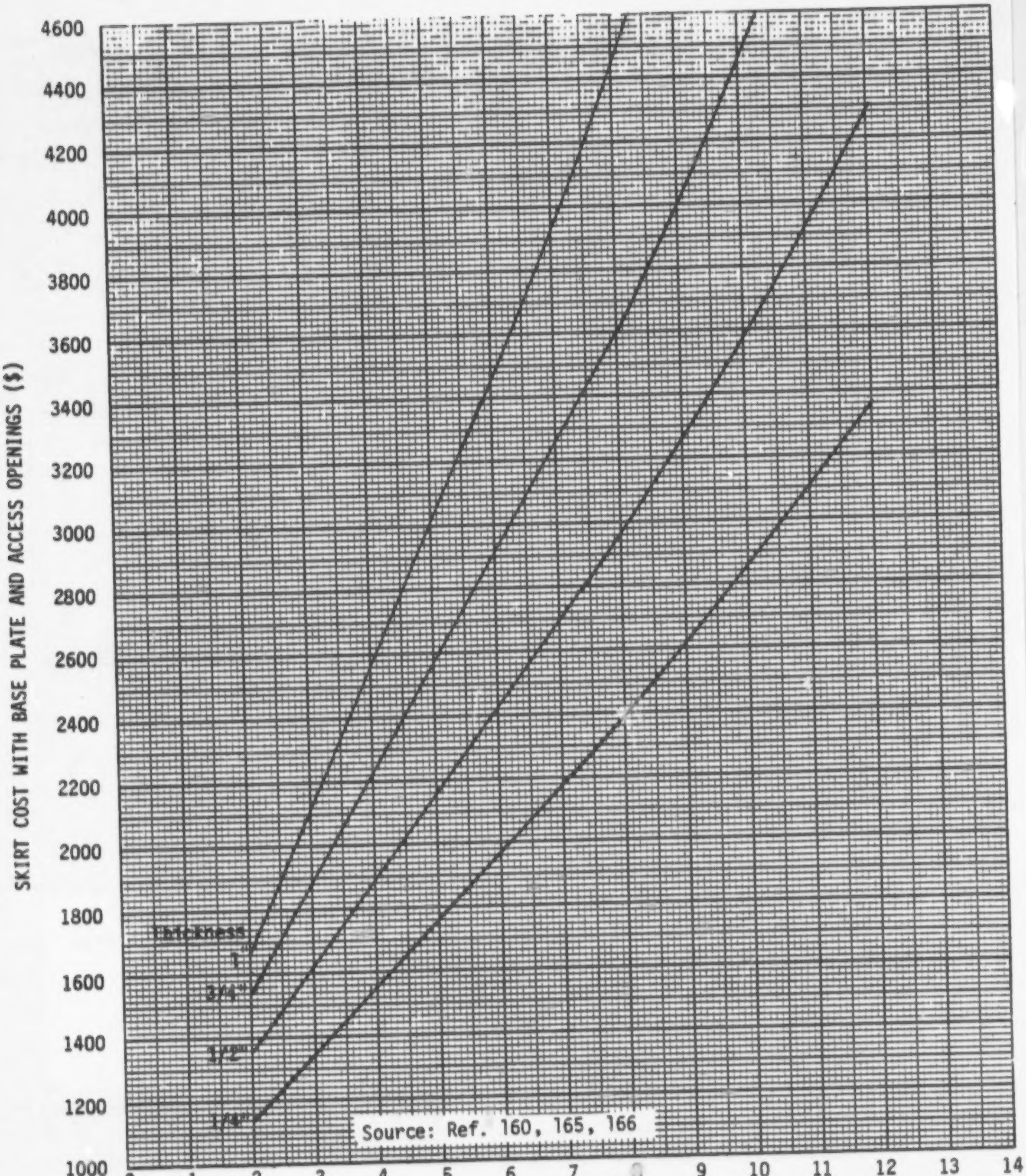
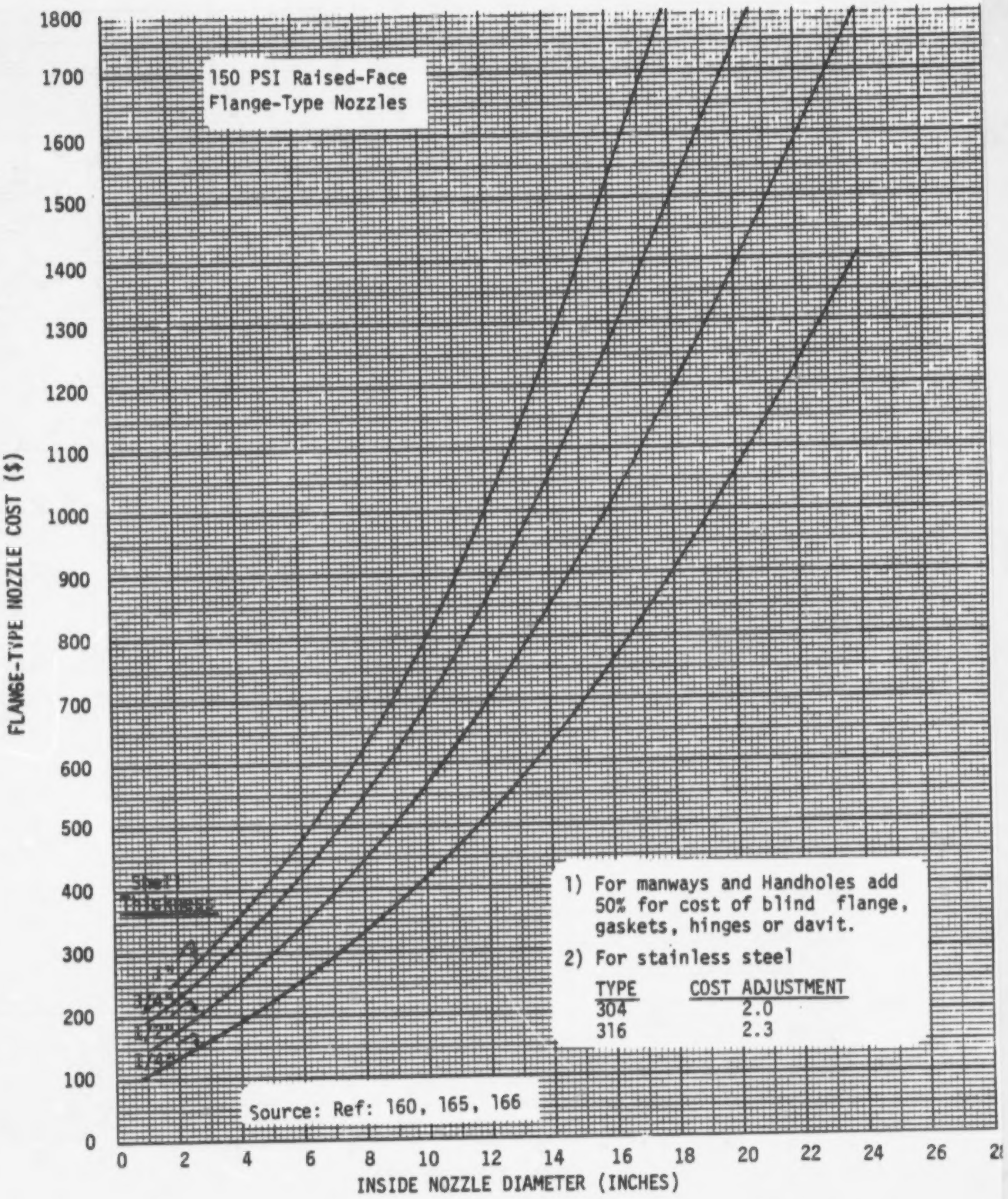


Figure 5-22 SKIRT AND SUPPORT COSTS FOR CARBON STEEL VESSEL



1) For manways and Handholes add 50% for cost of blind flange, gaskets, hinges or davit.

2) For stainless steel

TYPE	COST ADJUSTMENT
304	2.0
316	2.3

Source: Ref: 160, 165, 166

Figure 5-23 COST OF NOZZLES

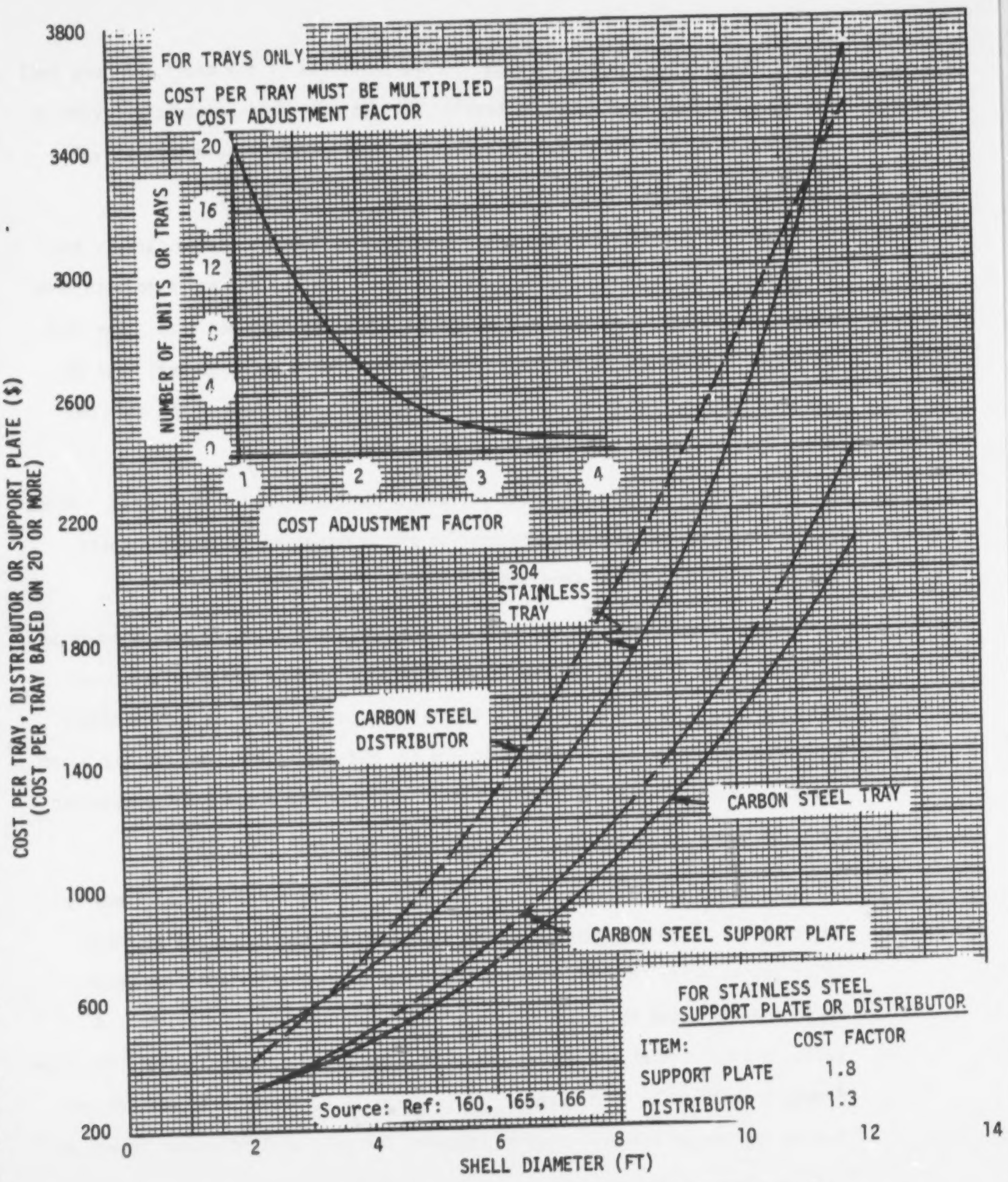


Figure 5-24 COST OF TRAY, SUPPORT PLATE OR DISTRIBUTOR

skirt should be approximately equal to the thickness of the shell. Figure 5-23 reflects the fabricated cost of nozzles for typical shell penetrations such as those required for the inlet and outlet for the gas and liquid, relief valve connections, pumpout alternates, spray inlets, and manways.

The cost of internal tower equipment such as support plates, trays, and distributors is shown in Figure 5-24. The indicated prices apply to both tray towers and packed towers and represent the installed cost per item. The cost of trays is based on quantities of 20 or more. For quantities less than 20, the unit tray cost must be multiplied by the cost adjustment. The cost per cubic foot of internal packing is shown in Table 5.5.

The summation of these costs represent the fabricator's shop costs. Added to this must be the fabricator's cost of engineering, administration costs, and profit as determined from Table 5.6.

As an example, the design calculations for a carbon steel packed tower as outlined in the illustrative problem of Reference 88 indicate that the tower diameter should be approximately 2 feet with a tower height of approximately 15 feet. The inlet gas flow rate is 520 cfm and the liquid flow rate is 3 gpm. The tower packing is to be 1-inch carbon steel raschig rings and the absorber is to be operated at ambient conditions of temperature and pressure.

Under these conditions, a 1/4-inch place thickness for the shell may be selected which would provide adequate allowance for corrosion. A suitable inlet gas velocity for this absorber would be approximately 1800 fpm which would require a gas inlet and outlet of approximately 8-inch diameter. A suitable liquid inlet and outlet pipe for 3 gpm would be approximately one inch. A manway of 18 to 24 inch diameter would normally be provided at the top and bottom for larger diameter towers, however, for this small diameter tower, a

Table 5.4 MINIMUM SHELL THICKNESS AT AMBIENT TEMPERATURE (CARBON STEEL)

Shell Diameter* (Ft)	2	4	6	8	10	12
Internal Pressure:						
Atmospheric	1/8"	1/8"	1/8"	1/8"	1/8"	1/8"
25" WG	1/8"	1/8"	1/8"	1/8"	3/16"	3/16"
50" WG	1/8"	1/8"	3/16"	3/16"	1/4"	1/4"
100" WG	1/8"	1/8"	3/16"	1/4"	5/16"	5/16"
10 PSIG	1/8"	1/8"	1/4"	3/8"	7/16"	1/2"
100 PSIG	1/8"	1/4"	3/8"	1/2"	3/4"	3/4"
200 PSIG	1/4"	1/2"	3/4"	1"	1-1/4"	1-1/2"

* For corrosion allowance add minimum of 1/8 inch. Thicknesses are for ambient temperatures and temperatures up to 600°F. Thickness correction factors for higher temperatures are: 1.04 for 700F; 1.14 for 750F; 1.35 for 800F (Ref. 165).

Table 5.5 COST OF TOWER PACKING (Ref. 160, 165, 166)

Type and Material	1 Inch ($/Ft^3)	1-1/2 Inch ($/Ft^3)	2 Inch ($/Ft^3)	3 Inch ($/Ft^3)	3-1/2 Inch ($/Ft^3)
Pall Rings:					
Carbon Steel	19	15	13	-	-
304 Stainless	54	43	35	-	-
Polypropylene	14	-	8	-	-
Intalox Saddles:					
Polypropylene	15	-	10	5	-
Porcelain	12	-	9	8	-
Raschig Rings:					
Carbon Steel	17	14	9	-	-
Porcelain	8	7	6	-	-

Table 5.6 ADDITIONAL COSTS FOR FABRICATOR'S ENGINEERING, PURCHASING, ADMINISTRATION AND PROFIT (Ref. 160, 166)

Total Cost of Fabricated Vessel	Cost Factor
Less than $ 5,000	0.25
$ 5,000 to $10,000	0.23
$10,000 to $20,000	0.20
$20,000 to $30,000	0.19
$30,000 to $50,000	0.18
$50,000 to $80,000	0.17
Over $80,000	0.16

12-inch hand hold can be provided at each end of the tower. A drain in the bottom head of the tower should also be provided for draining, flushing and cleanout.

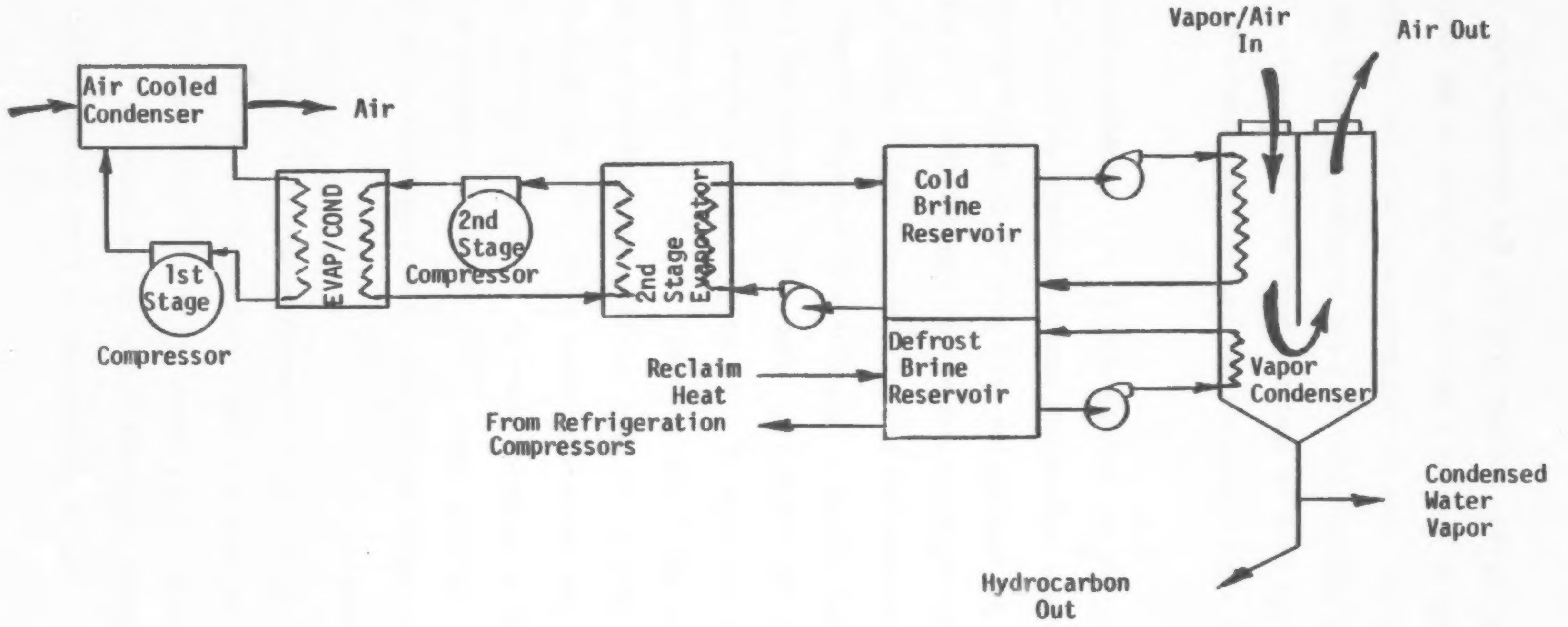
Using Figure 5-21 the cost of the basic vessel is $420 for the heads plus $52 per foot of shell or $1200. The cost of the skirt, as determined from Figure 5-22, is $1140. The installation of nozzles for the various vessel penetrations results in a cost of $2580 for three liquid nozzles at $120 each, two gas inlet/outlet nozzles at $330 each, and two hand holes with blind flanges at $780 each.

The tower internals would consist of a packing support plate and two distributors spaced at 5 foot intervals plus the internal packing material. The cost of the support plate and distributors, as determined from Figure 5-24, is estimated to be $1220. The volume of packing required for a 15-foot tower with a 2-foot diameter is approximately 47 cubic feet and the estimated cost of the packing, as determined from Table 5.5, is approximately $800. The total fabricated cost of the packed tower is therefore $6940. The fabricator's sell price including engineering, administration costs, and profit, but less taxes and freight, is determined from Table 5.6 to be $6940 x 1.23 or $8540.

5.7 Refrigeration

Removal of gaseous contaminants in a process stream can be accomplished by cooling the gas stream to condense and remove the contaminants. Refrigeration may be used alone or be combined with other processes for the removal or recovery of gaseous pollutants. For instance, in the removal and recovery of hydrocarbon vapors from the transfer operations at teminals and bulk plants, refrigeration can be used singly to condense the vapors at atmospheric pressure or it can be used in conjunction with a compressor for condensation and/or absorption of the vapors at higher pressures and more moderate temperatures. In absorption systems, refrigeration can be used to condition the solvent by increasing its gas solubility characteristics at lower temperatures, thus permitting both the solute and solvent to be the same product but in different phases, i.e., gas and liquid.

Vapor recovery systems utilizing refrigeration alone at atmospheric conditions usually consist of a refrigeration unit, a heat exchanger/evaporator, storage tanks for the chilled and defrost brines, and a vapor condenser. For low temperature applications, the refrigeration unit is normally a compound or cascade multistage system providing temperatures to as low as -250°F. In general, compound systems are used for systems requiring temperatures to approximately -100°F and cascade systems are used for temperatures below -100°F. The recovery of hydrocarbons typically found in the transfer operations of petroleum products require temperatures of approximately -110°F and cascase refrigeration systems are normally used. In the cascade system, shown in Figure 5-25, the condenser of one refrigeration stage acts as the evaporator for the second stage to produce these lower temperatures. The evaporator for the final stage of refrigeration is the heat exchanger/evaporator where a chilled brine is circulated and cooled. A storage tank is provided for the chilled brine as a low temperature reservoir of coolant for the vapor condensor. The gas stream mixture of air and hydrocarbon vapors enters the vapor condenser where the hydrocarbons having boiling temperatures above approximately -100°F are condensed and collected at the bottom of the vapor condenser. In the condensing process, moisture in the gas stream is also collected as frost on


Air Cooled Condenser
Air
1st Stage
Compressor
EVAP/COND
2nd Stage
Compressor
2nd Stage Evaporator
Reclaim Heat
From Refrigeration Compressors
Cold Brine Reservoir
Defrost Brine Reservoir
Vapor/Air In
Air Out
Vapor Condenser
Condensed Water Vapor
Hydrocarbon Out

Source: Edwards Engineering Corp.

Figure 5-25 Cascade Refrigeration System for Vapor Recovery

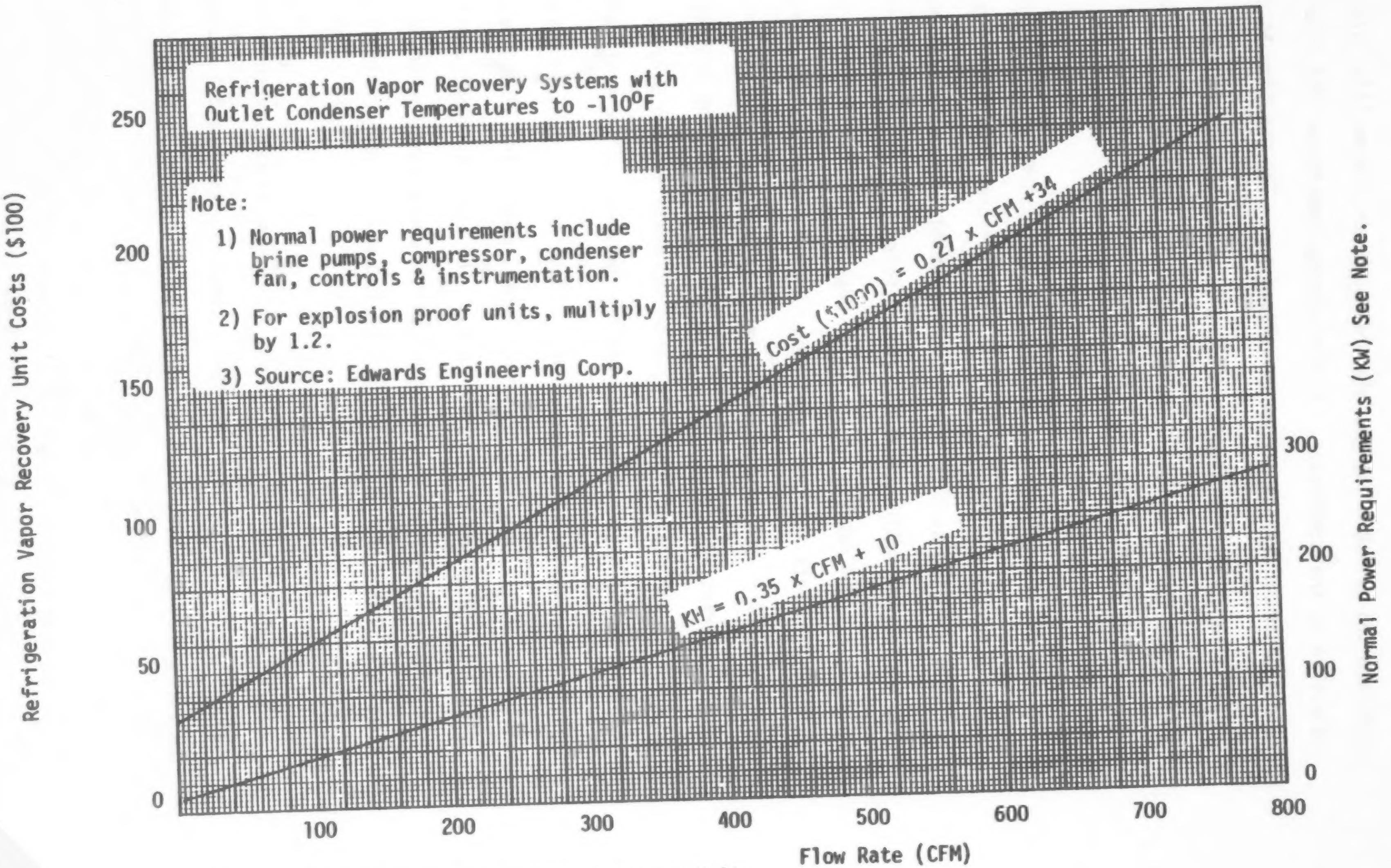
the condensing surface and periodically the condenser must be defrosted. This is accomplished by passing a defrost brine through the vapor condenser for a short time period. The defrost brine acts as a heat exchange medium by removing heat from the refrigeration unit and transferring it to the vapor condenser. A separate storage tank is used as a warm brine reservoir. For continuous vapor recovery, two vapor condensers can be used; one condensing while the second is defrosting.

Refrigeration can also be used as an intermediate stage in a combined process to remove hydrocarbon vapors. Systems utilizing refrigeration in this capacity are the Compression-Refrigeration-Condensation systems (CRC) and the Compression-Refrigeration-Absorption systems (CRA). In the compression-frigeration-condensation process, the gas stream containing hydrocarbon vapors is first passed through a saturator with recovered product to saturate the gas stream beyond the flamability range. The saturated gas stream is then passed through the first stage of a two stage compressor where the gas is compressed. An intercooler and liquid/gas separator are provided between stages to cool and condense some of the more volatile vapors before the gas stream is delivered to the second compressor stage. The gas leaving the compressor passes through a condenser where it is cooled to permit subsequent condensation of the remaining vapors. This condensate together with the condensate from the intercooler are returned to storage tanks or to the saturator as recovered product.

In the Compression-Refrigeration-Absorption system, the flow scheme is essentially the same with the exception of the replacement of the condenser with an absorber. The absorber in this process, however, is the primary unit and the remaining components serve to condition the liquid and vapor entering the absorber. The vapor-laden gas is first passed through a saturator to saturate and maintain the gas mixture above the flamability level before it is delivered to the compressor. A single stage compressor and aftercooler are used to precondition the gas stream for absorption. The gas then enters the absorber where it is sprayed by liquids chilled in a refrigeration unit. The absorption of the vapors by the liquid is promoted by moderate pressures and lower temperatures so that the remaining gases are essentially free of hydrocarbons and can be vented to the atmosphere.

The CRC and CRA systems are proprietary systems which have been custom designed and fabricated for specific applications. These systems are not actively marketed at this time. Systems using only refrigeration can be adapted to many applications and the efficiency or vapor recovery capability of these systems depends on the vapor pressure and temperature characteristics of the pollutants and the gas stream. Refrigeration systems are particularly well suited for applications such as the recovery of hyrdrocarbon vapors from gasoline marketing operations. These systems are sold as packaged units containing all the piping, controls, and components and are usually provided skid-mounted with an appropriate weather enclosure. The auxiliary equipment required to provide a complete vapor collection and recovery system might consist of a gas holder, liquid storage tanks, pumps, and piping between the pollutant source and the storage tanks. The size and subsequently the cost of a vapor recovery unit will depend on the operational schedule, process flow rate, level of hydrocarbon emissions and the gas and liquid storage capacities.

The costs of refrigeration vapor recovery systems are shown in Figure 5-26. The cost of the unit includes a complete skid mounted package containing the refrigeration unit, brine storage, two condensing units, and pumps, valves



Refrigeration Vapor Recovery Systems with Outlet Condenser Temperatures to -110^{0}F

Note:

1) Normal power requirements include brine pumps, compressor, condenser fan, controls & instrumentation.
2) For explosion proof units, multiply by 1.2.
3) Source: Edwards Engineering Corp.

Figure 5-26 Refrigeration Vapor Recovery Units

and controls. These units are priced according to the continuous gas flow rate in cfm which is processed. In transfer operations, this represents the displaced volume of gas corresponding to the maximum continuous flow rate of product pumped; or, in terms of cfm, one cfm is equal to 7.48 gpm. The condensing temperature for these units is approximately -100 to -110°F which is sufficient to condense most of the heavier hydrocarbons.

For gasoline vapor recovery, the units have the capacity of recovering a minimum of 90% of the hydrocarbon vapor when the vapor entering the condenser consists of 35% gasoline hydrocarbon by volume; and of recovering 70% of the hydrocarbon vapor when the vapor entering the condenser consists of 15% gasoline hydrocarbon by volume. At all feed conditions the partial pressure of the hydrocarbons in the vapor leaving the vapor recovery units is approximately 0.38 psia. The recovery rate of other hydrocarbons, such as benzene or toluene, will depend on the partial pressure of the hydrocarbons in the feed stream and the corresponding vapor pressure of the hydrocarbons at the outlet temperature of approximately -110°F

The pressure drop through the vapor condensers ranges from approximately 1 inch W.G. when the condenser is free of frost to 4 inches W.G. when the condenser is ready for defrosting. The estimated normal power consumption for the units excluding fan/blower power costs for the gas stream and pump power requirements, if any, for the recovered product, is also shown in Figure 5-26. The average service and maintenance costs for these units are estimated to be approximately $150 per month based on an optional preventative maintenance service provided by the manufacturers. The cost of this service is the same for all units.

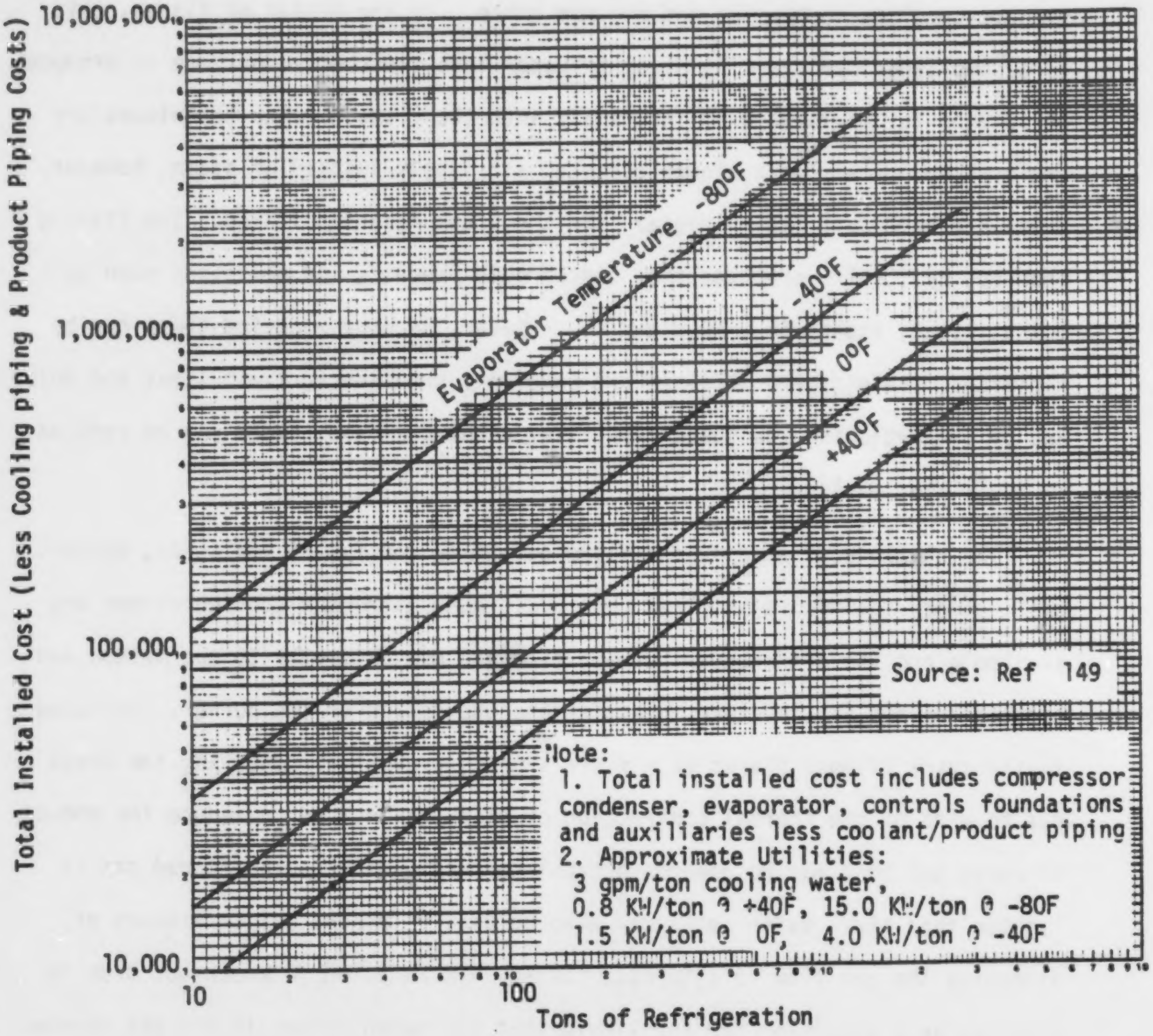
The costs shown in figure 5-26 are specifically for refrigeration vapor recovery units used to recover hydrocarbons from gas streams. These systems include vapor condensers, defrost equipment, and other ancillary components required for these applications. The cost of industrial vapor compression refrigeration systems used for cooling other products are shown in figure 5-27. These costs represent the complete system fully installed including the compressor, condenser, evaporator, controls, foundations and all auxiliaries except the piping runs for product or cooling lines. These systems are rated in tons of refrigeration (12,000 Btu per hour per ton of refrigeration) at various evaporator temperatures. As the evaporator temperature is lowered, the capacity of a given refrigeration unit decreases. In air cooling systems similar to the solven recovery units shown in figure 5-25, the approximate relationship between gas flow rate and tons of refrigeration is given by

$$\text{Tons refrigeration} = \frac{4.5\,Q\,\left[(.24 + 0.45\,W)\,\Delta T + 1076\,\Delta W\right]}{12{,}000}$$

where Q = gas flow rate, SCFM
W = humidity ratio, lb water/lb dry air
ΔT = inlet air temperature minus evaporator temperature, °F

5.8 Flares

Flares are used predominantly in refineries and in the petrochemical industry to burn waste gases which normally are not economically recoverable. In many cases flares are used in the event of a process upset or some other emergency condition where excess gases and vapors must be vented immediately. Under these circumstances, flares are normally used intermittently with possible long periods of disuse.



Source: Ref 149

Note:
1. Total installed cost includes compressor condenser, evaporator, controls foundations and auxiliaries less coolant/product piping
2. Approximate Utilities:
3 gpm/ton cooling water,
0.8 KW/ton @ +40F, 15.0 KW/ton @ -80F
1.5 KW/ton @ 0F, 4.0 KW/ton @ -40F

Figure 5-27 Installed Cost of Industrial Vapor Compression Refrigeration Systems

Flares are generally categorized as either ground or elevated flares. By elevating the flare, the open flare can be removed from potentially dangerous ground areas and the products of combustion can be dispersed above the working areas to reduce the effects of noise, smoke, and objectionable odors. As in all combustion processes, an adequate air supply and good mixing are required to produce complete combustion and minimum smoke. In the design of flares, this is accomplished by injecting steam or water into the combustion zone to produce turbulence for mixing and to induce air into the flame. Other techniques are employed which rely on a blower assisted air supply instead of steam, however, these are used to a lesser degree than the steam assisted flares. The flaring process, by itself, produces some undesirable products and emissions such as noise, light, smoke, SO_x, NO_x, and CO, however, by proper design these can be minimized. Shields and mufflers are sometimes provided to limit light and noise and by proportioning the steam flow rate to the gas flow, smoke can be reduced to invisible levels.

The elements of an elevated flare generally consist of the stack, burner, seal, pilot, ignition system and controls. Many different configurations are available and the differences between each are due primarily to the method and location of the air or steam injection and the design of the burner. Included in the stack of most flares is a flare seal to prevent air entering the stack due to wind or the thermal contraction of stack gases, and to reduce the amount of purge gas that may be needed to expel combustibles when the flared gas is lighter than air. Water seals may also be used as a seal and as a means of directing the gas flow to alternate flares. In addition, a knock-out drum is provided as a separator for any liquid that may be entrained in the gas stream. The knock-out drum and water seal are usually incorporated into the same vessel. Elevated flares can be free standing, guyed, or structurally supported by a derrick. Free standing flares provide ideal structural support. However, for very high units the costs increase rapidly and the foundation and nature of the soil must be considered in both the static/dynamic and cost analysis. Derrick supported flares can be built as high as required since the system load is spread over the legs of the derrick. This design provides for differential expansion between the stack, piping and derrick. The guy supported flare is the simplest of all the support methods. However, a considerable amount of land is required since the guy wires are widely spread apart. In addition the waste gases must be near ambient temperature since any expansion or contraction due to temperature differences will change the tension in the guy wires and cause structural damage.

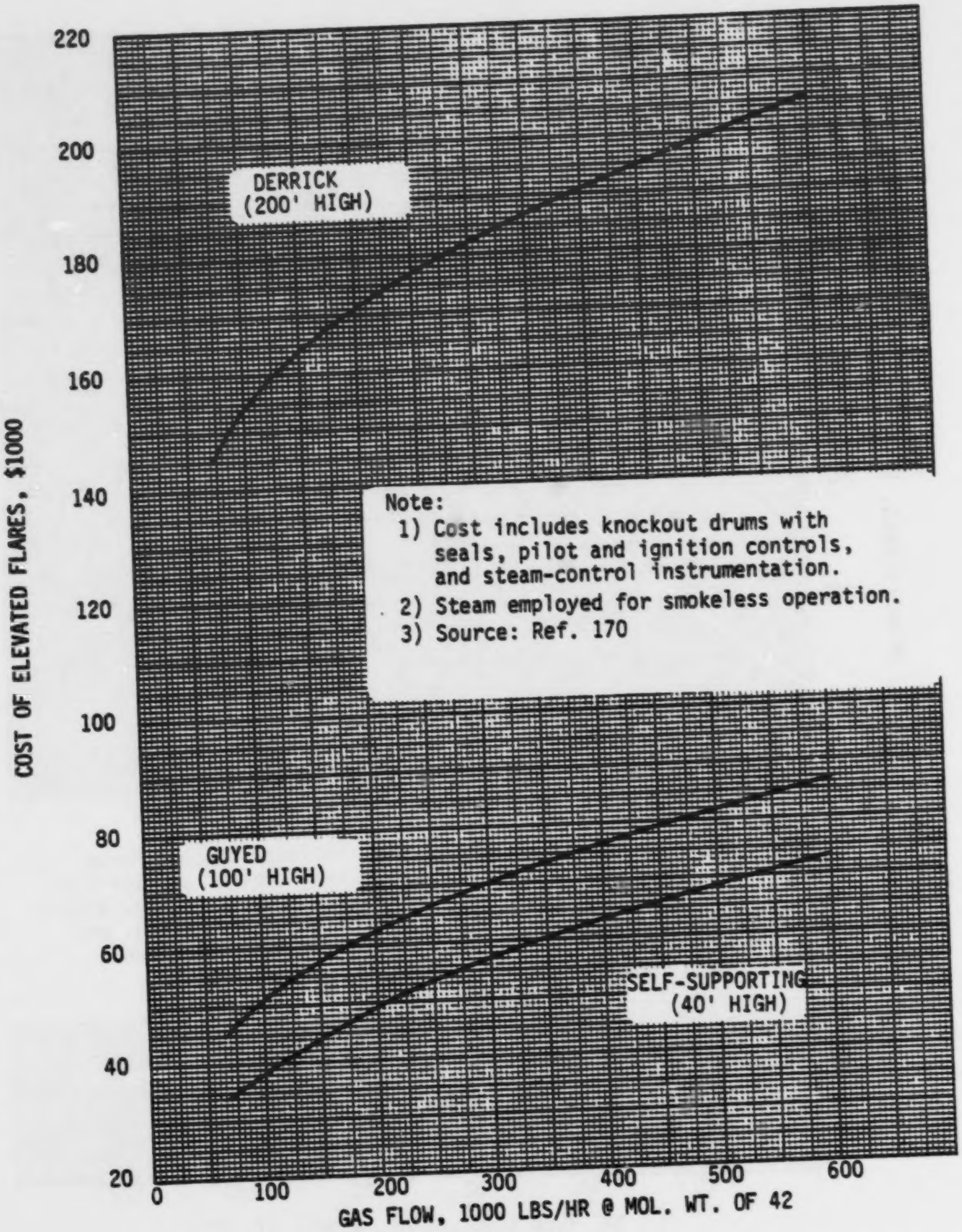
Some flares are provided with auxiliary fuel to oxidize hydrocarbon vapors when the gas stream falls below the flammability range or can no longer sustain a flame. Control of the auxiliary fuel is automatic, and this type of system is ideal for processes with large fluctuations of hydrocarbon gas compositions.

Ground flares are used to dispose of waste liquids and gases. These flares may contain several nozzles or burners and combustion can occur inside a refractory chamber or in an open pit. Ground flares and elevated flares can be used together in an integrated system whereby excess waste gases can be diverted from ground flares to an elevated flare.

Elevated flare diameters are normally sized to provide vapor velocities at maximum throughput of about 20 percent of the sonic velocity in the gas. The maximum pressure drop for a flare is limited to approximately 2 psig (60 inches WG). The height of a flare is based on the ground level limitations of luminosity, thermal radiation, noise, height of surrounding structures and the dispersion of the exhaust gases. A discussion of these items can be found in References 88 and 138. Self supporting flares should be used for flare tower heights of up to 50 feet, guyed towers to 100 feet, and derrick towers above 100 feet. The operating costs for a flare will depend on the quantity of purge gas and steam required and a discussion of these requirements is given in Reference 138. For general consideration, the quantity of steam required can be assumed to be 0.4 pounds of steam per pound of hydrocarbon. For specific applications, Reference 138 should be consulted. The use of steam as a smoke suppressant for elevated flares can represent 92 to 98 percent of the operating costs.

The capital cost of flares depends on the degree of sophistication desired and the amount of appurtenances selected such as knock-out drums, seals, controls, ladders, platform, etc. The basic structure and support of the flare, the size and height, the flow rate, and the auxiliary equipment are controlling factors in the cost of the flare. The capital investment will also depend on the availability of utilities such as steam and natural gas, the variations in the composition of the waste gases, and the frequency of flaring. Typical costs for elevated flares range between $30,000 and $100,000 (Ref. 138). Ground flares can be as much as ten times the cost of an elevated flare for the same capacity range. Blower assisted flares (forced draft flares) are between two to three times the cost of an equivalent conventional elevated flare (Ref. 138).

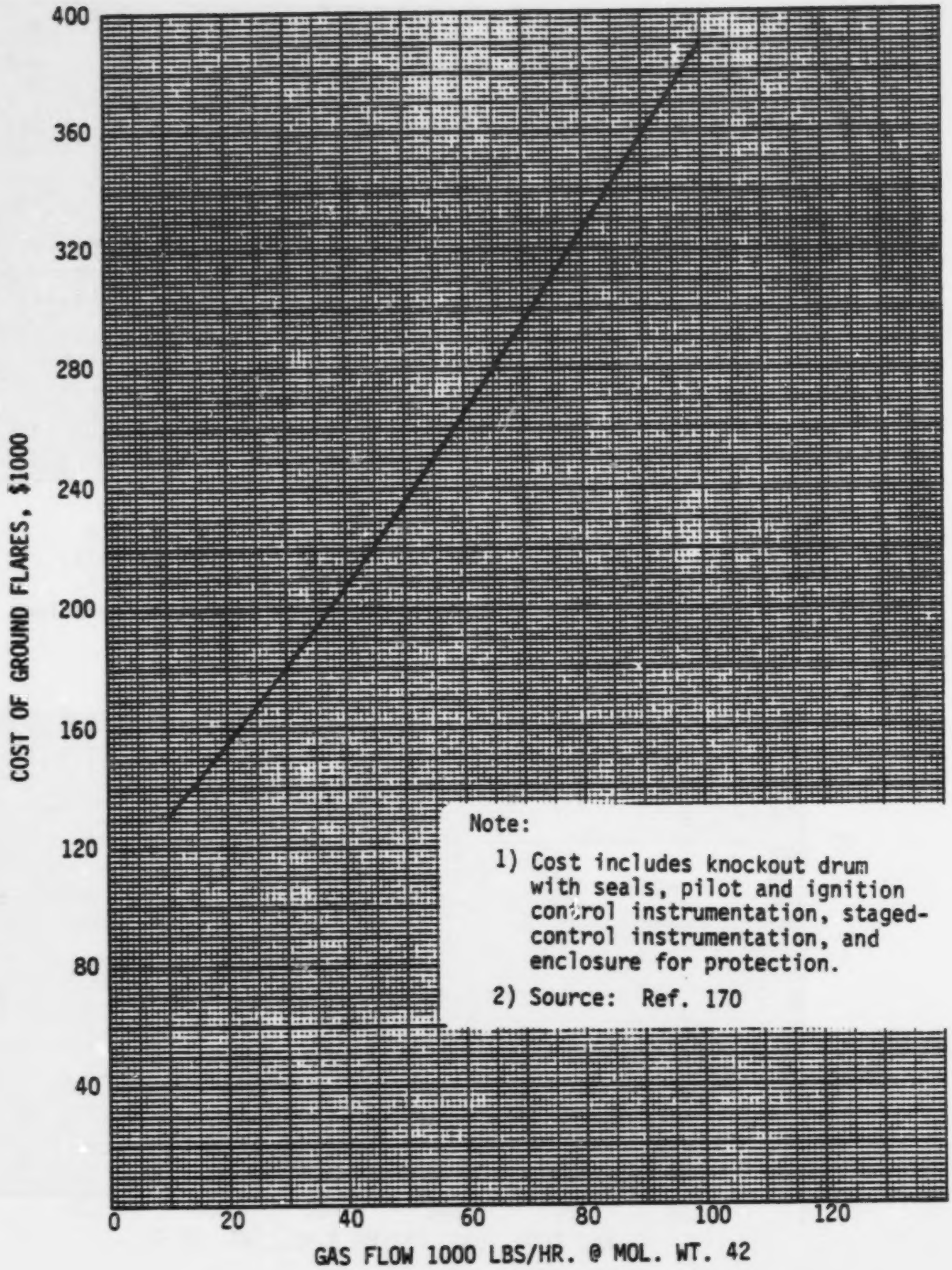
Figure 5-28 shows typical costs of elevated flares (self-supporting, guyed, and derrick) versus gas flow rates. The gases are assumed to have an average molecular weight of 42. For comparison purposes, a 12-inch diameter flare (Figure 5-28) would be designed for an approximate gas flow of 70,000 lbs/hr, an 18-inch diameter for 200,000 lbs/hr, and a 30-inch diameter for 600,000 lbs/hr. The cost of ground level flares in shown in Figure 5-29.



Note:

1) Cost includes knockout drums with seals, pilot and ignition controls, and steam-control instrumentation.
2) Steam employed for smokeless operation.
3) Source: Ref. 170

Figure 5-28 COST OF ELEVATED FLARES



Note:

1) Cost includes knockout drum with seals, pilot and ignition control instrumentation, staged-control instrumentation, and enclosure for protection.

2) Source: Ref. 170

Figure 2-29 COST OF GROUND LEVEL FLARES

Section 6

SAMPLE COST ESTIMATES AND SYSTEM COST COMPARISON

To illustrate use of the manual, a case study on rotary kiln air pollution control is presented here. Since this manual provides very little guidance regarding the design of air pollution control systems, it is essential that the user have prepared in advance an engineering design for control of the pollutant source. Care should be taken in the design because a poor design is likely to result in unrealistic costs. There may be many system configurations that will satisfy the technical requirements, but only one or two will cost the least. In the example presented here, the engineering design is intended to demonstrate the use of the manual and is simplified in the interest of clarity and brevity. Hence the design may not be optimal. The reader should however, concentrate on understanding how the manual is used. Engineering design techniques may be found in EPA Pub. AP-40, Air Pollution Engineering Manual. (see Appendix C, No. 88).

Lime (CaO or $CaO \cdot MgO$) is the product of the calcination of limestone ($CaCO_3$ or $CaCO_3 \cdot MgCO_3$). Lime manufacturing involves several sources of pollutants. The sources include:

a) Quarrying - stripping, drilling, blasting, loading, and hauling.

b) Stone processing - crushing, pulverizing, screening, and conveying.

c) Limestone calcining (kilns)

d) Lime hydration, drying, and bagging.

e) Fugitive dust, roads, stockpiles, transportation, etc.

This section is concerned solely with rotary lime kiln operations. Kilns are basically of two types: vertical and rotary. Rotary kilns are used by the majority (80-90%) of lime plants and they represent the largest single source of pollutants in the lime industry. The pollutants are predominately particulate matter. Broadly speaking, about 30% of the dust from rotary kilns is less than 10μ and the mean size is 30μ. The exhaust temperature from rotary kilns depends on the length of the kiln and other process variables. Lime kiln exhaust gas is usually cleaned with venturi scrubbers or fabric filters, although electrostatic precipitators may also be used. This case study will show cost estimation for all three methods. The following conditions are assumed:

- o A typical 250 TPD rotary kiln to be controlled at 1000 ft elevation.
- o Required control efficiency of 99+%.
- o Exhaust gas from kiln: 30,000 SCFM or 88,300 ACFM @ 1100F. *
- o Control device to be located 200' from source.
- o Direct exhaust from kiln.
- o Duct velocity - 4000 fpm to prevent fallout
- o Surrounding terrain does not impose unusual constraints on system design and stack height (50').

CASE A - OUTLINE OF ENGINEERING CALCULATIONS FOR FABRIC FILTER

Establish overall engineering design as follows:

a. Use polyester (275F) or glass bags (550F).
b. A/C ratio = 2 for glass bags.
   = 3 for polyester bags.
c. Suction baghouse:
   - reverse air, insulated for glass bags
   - mechanical shaker, insulated for polyester bags
d. Radiant coolers next to source.
e. Mechanical cyclone just prior to baghouse
f. Dilution air port provided for temperature modulation.
g. By-pass damper omitted.

---

* Composition: N_2-60%, CO_2-24%, H_2O-15%, O_2-1% (by volume).

Figure 6-1 shows the system layout for a fabric filter operation. The following discussion outlines how the design parameters are obtained for each stage along the system.

Stage 1: Direct exhaust from kiln, determine carbon steel elbow duct size:

$$\frac{88300\ \text{ACFM}}{4000\ \text{fpm}} = 22.1\ \text{Ft}^2$$

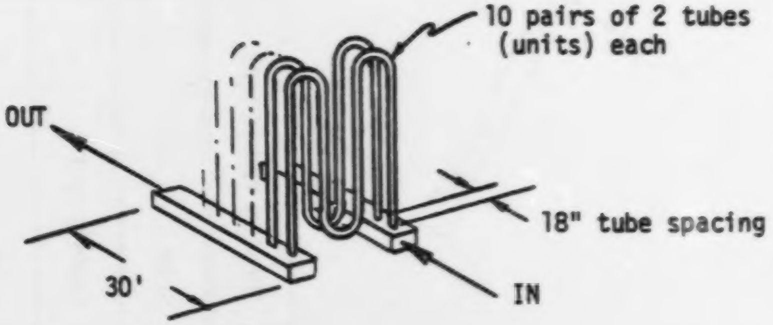
Hence, 64" duct (22.3 ft^2) may be used, giving:

$$\frac{88300\ \text{ACFM}}{22.3\ \text{ft}^2} = 3960\ \text{fpm}$$

Stage 2: a. Assume no temperature drop from kiln outlet to inlet of radiant cooler. Estimate that about 600 F temperature is required out of the cooler. Try initial 5000 fpm through two 18" U tubes in series. Thus:

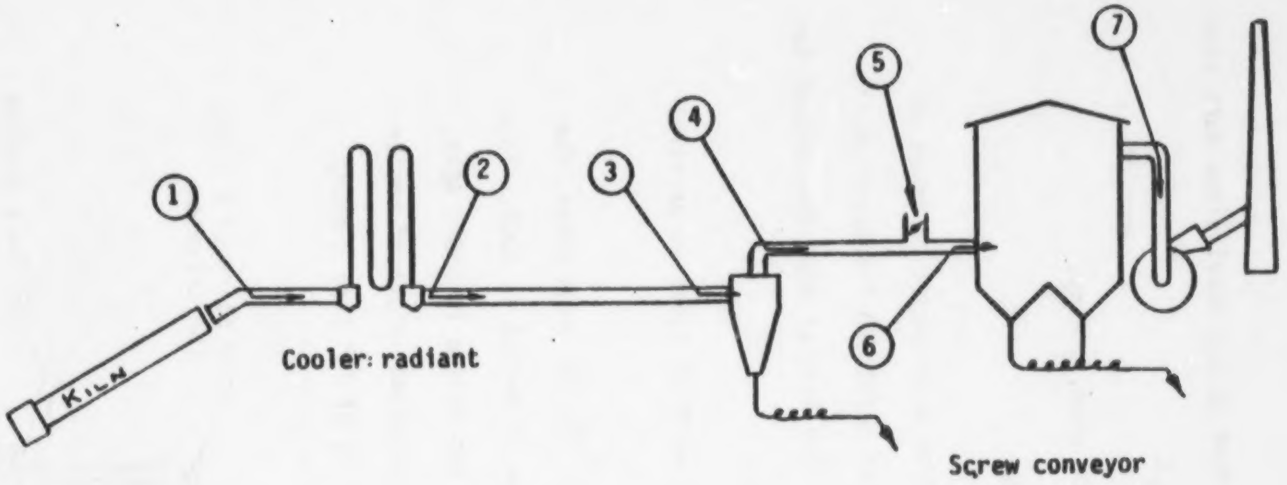
$$\frac{88300\ \text{ACFM}}{1.767\ \text{ft}^2/_{\text{tube}} \times 5000\ \text{fpm}} = 10\ \text{pairs of tubes in parallel}$$

From engineering calculations* for 40' high tubes, the temperature drop for two tubes in series is 500F. Thus exit temperature is 600F and gas volume is 60000 ACFM. Pressure drop is 2.1" W.G. Estimated length of cooler is 30 feet based on tube spacing of 18" (see sketch).



---

[*] Heat transfer calculation methods may be found in the EPA publication AP-40. See Appendix C, reference 88.


Kiln
Cooler: radiant
Screw conveyor
①
②
③
④
⑤
⑥
⑦

DESIGN PARAMETERS	1	2	3	4	5	6	7
SCFM	30,000	30,000	30,000	30,000	38,600[b]	30,000[a] 68,600[b]	30,000[a] 68,600[b]
TEMPERATURE	1100 F	600 F	530 F	500 F	100 F[b]	500 F[a] 275 F[b]	500 F[a] 275 F[b]
ACFM	88,300	60,000	56,000	54,300	40,800[b]	54,300[a] 95,100[b]	54,300[a] 95,100[b]
DUCT DIAMETER	64"	52"	52"	52"	52"	Neglect	Neglect
STATIC PRES. (" WG)	Kiln Draft	-2.1"	-2.7"	-8.7"	-	-	-14.7"

a - glass bag
b - polyester bag

Figure 6-1 FABRIC FILTER SYSTEM DESIGN

From Chapter 3 of ref. 88, the quantity of heat removed from the cooler is determined by: $Q = w(\Delta h)$ where w is in lbs/hr or scfh and Δh is in Btu/lb or Btu/scf. The overall heat transfer coefficient (U) is determined by calculating the inside and outside film coefficients for an 18-inch diameter tube with a velocity of 5000 fpm. The log mean temperatures difference (T_m) is calculated using an assumed ambient temperature of 100°F and an inlet temperature of 1100°F and an outlet temperature of 600°F. The total surface area required is then determined by: $A = Q/U(\Delta T_m)$. Since there are 10 pairs of tubes (units) in parallel, the developed length of each will be: $L = A/10 \pi D$ where D is the diameter (1.5 ft). The height of the cooler is calculated by dividing the developed length L of each pair by the number of vertical columns in each pair. For pressure drop calculations, also see Chapter 2 of Ref. 88.

b. Determine carbon steel duct diameter

$$\frac{60000 \text{ ACFM}}{4000 \text{ fpm}} = 15 \text{ ft}^2$$

Hence 52" duct (14.7 ft^2) may be used, giving:

$$\frac{60000 \text{ ACFM}}{14.7 \text{ ft}^2} = 4080 \text{ fpm}$$

Stage 3. Cooling of gas will take place over 200-30 = 170 ft. of duct. The calculations used in stage 2 to determine the size of the U-tube cooler are applied again. The surface area of a 52" duct, 170 ft long is calculated to be 2314 sq. ft. The overall heat transfer coefficient is determined using a velocity of 4080 fpm and a duct diameter of 52". An outlet temperature at the end of the duct must first be assumed to determine the log mean temperature difference. If the calculated and assumed temperatures differ significantly, the procedures must be reiterated until both temperatures are approximately the same. For gas temperatures about 600^{o}F and a velocity of 4000 fpm, a temperature drop of 0.4 degrees per ft. is a reasonable assumption. Using the overall heat transfer coefficient, assumed log mean temperature difference, and the surface area, the total heat transferred can be calculated. The outlet temperature is determined from the change in enthalpy of the gas stream. In this case, the outlet temperature is found to be 530 F. This is reasonably close to the assumed temperature. The pressure drop through 170' of duct can be determined from the friction charts in chapter 2 of reference 88, corrected for the difference in density. The pressure drop is found to be approximately 0.6" W.G. The new ACFM at the end of the duct is:

$$60000 \text{ ACFM} \times \frac{990 \text{ R}}{1060 \text{ R}} = 56000 \text{ ACFM}$$

Expansion joints are usually provided between major components such as coolers, mechanical collectors, etc.; therefore, two expansion joints are required, one 52", the other 64".

Stage 4. Select two mechanical collectors in parallel to handle 28000 ACFM each. For 6" pressure loss, the inlet area is 8.5 ft^2 and the critical partical size is 24 microns. Mechanical collectors also provide some degree of cooling. Manufacturers usually supply the expected heat losses for specific applications. For gas temperatures at 500 F, a temperature drop of approximately

30 F can be assumed. Thus, the new gas volume after the mechanical collectors is:

$$56000 \text{ ACFM} \times \frac{960 \text{ R}}{990 \text{ R}} = 54{,}300 \text{ ACFM}$$

Stage 5. Dilution air port is provided for baghouse for modulation of gas temperature. For glass bags, no dilution air will generally be required. For polyester bags, dilution air is estimated as follows (neglecting the difference in heat capacities):

$$(30{,}000 \text{ SCFM})(500\text{F}) + D\,(100\text{F}) = (30000+D)(275\text{F})$$

$$D = 38{,}600 \text{ SCFM}$$

Stage 6. Hence total gas volume is 68,600 SCFM or 95,100 ACFM @ 275F for polyester bags, and is 54,300 ACFM @ 500F for glass bags.

The baghouse is sized as follows:

a. For glass bags:

$$\frac{54300 \text{ ACFM}}{2.0 \text{ A/C}} = 27150 \text{ ft}^2 \text{ net cloth area.}$$

b. For polyester bags:

$$\frac{95100 \text{ ACFM}}{3.0 \text{ A/C}} = 31700 \text{ ft}^2 \text{ net cloth area}$$

Baghouses are nominally sized for 6" W.G. Neglect temperature drop through the baghouse.

Stage 7. Total pressure drop across system is:

Radiant cooler	2.1" W.G.
Ductwork	.6
Mechanical collector	6.0"
Baghouse	6.0"
	14.7" W.G.

Size fans for 54,300 ACFM and 95,100 ACFM for glass and polyester bags respectively. Assuming a stack height requirement of 50' and a design exit stack velocity of 4000 fpm, select stack diameters of 50" and 66" respectively. Dust storage is also assumed to be at or near the collection site so that 50' of 9" screw conveyor is adequate for dust removal.

COST ESTIMATE OF FABRIC FILTER SYSTEM

a.	(1) 64" carbon steel elbow, 1/4" thick (Figure 4-10) -	$ 2,200
b.	(20) units of 18" carbon steel radiant cooler 40' high (Figure 4-24) -	71,000
c.	(170) feet of 52" carbon steel duct 3/16" thick (Figure 4-7) -	11,900
d.	(2) carbon steel, 10 Ga., mechanical collectors with inlet area = 8.5 ft^2 -	19,240

Collector (Figure 4-17)	$ 4,360
Support (Figure 4-19)	2,960
3/16" Hopper (Figure 4-20)	800
Scroll (Figure 4-21)	1,500
Total Each	$ 9,620

e.	(1) 3/16" transition to mechanical collector (Figure 4-10) -	800
	(2) expansion joints, one 52" one 64" (Figure 4-12) -	7,300
	Sub-Total	$112,440

(Filter with glass bags)

f.	(1) 52" carbon steel dilution air port, 3/16" thick (Figure 4-25) -	$ 6,200

g.	(1) 27,150 ft^2 net cloth area, continuous, reverse air, insulated baghouse (Figure 5-13) -	162,000
h.	Suction add-on (Figure 5-13) -	10,000
i.	(1 set) 27,150 X 1.17 = 31,765 sq ft gross area glass bags (Table 5.1) -	14,300
j.	(1) 54,300 ACFM backwardly curved Class IV fan at 14.7" W.G. actual (29" standard) (Figure 4-33) -	7,000
k.	(1) 1,800 RPM, 180 HP drip proof motor (Figure 4-34) -	3,000
l.	(1) Magnetic starter with circuit breaker (Figure 4-34) -	1,800
m.	(1) 50" diameter, 50' high stack, 1/4" thick (Figure 4-41) -	5,200
n.	(50) feet of 9" screw conveyor (Figure 4-26)	3,900
	Sub-Total	$213,400

(Filter with polyester bags)

f.	(1) 66" carbon steel dilution air port, 1/4" thick (Figure 4-25) -	$ 8,600
g.	(1) 31,700 ft^2 net cloth area, continuous, mechanical shaker baghouse (Figure 5-12) -	116,000
h.	Suction add-on (Figure 5-12) -	$ 10,000
i.	Insulation add-on (Figure 5-12) -	58,000
j.	(1) set 31,700 X 1.17 = 37,089 sq ft gross area Dacron bags (Table 5.1) -	12,980
k.	(1) 95,100 ACFM backwardly curved Class IV fan at 14.7" WG actual (29" standard) (Figure 4-33) -	10,000

l.	(1) 1,800 RPM, 300 HP, drip-proof motor (Figure 4-34) -	4,800
m.	(1) magnetic starter with circuit breaker (Figure 4-34) -	3,000
n.	(1) 66" diameter, 50' high stack, 1/4" thick (Figure 4-41) -	6,400
o.	(50) feet of 9" screw conveyor (Figure 4-26) -	3,900
	Sub-Total	$233,680

Total capital and annualized costs for the fabric filter system are summarized below; see Section 3 for installation, maintenance and operating cost factors with no cost adjustment.

CAPITAL COSTS

Item	Glass bags	Polyester bags
Auxiliary equipment and control device	$325,840	$346,120
Instruments and Control (10%)	32,580	34,610
Taxes and freight (8%)	26,070	27,690
Purchased Equipment Cost	$384,490	$408,420
Direct and indirect installation costs (117% of equipment costs)	449,850	477,850
Total Installed Cost	$834,340	$$886,270

ANNUALIZED COSTS

(8000 hrs/yr. or 1000 shifts)

Item	Glass bags	Polyester bags
Operating labor (2 hr/shift)	$18,100	$18,100
General maintenance (1 hr/shift & mat'l.)	34,640	34,640
Replacement bags (life 1.5; 2 years)	9,530	6,490
labor for replacement bags	9,530	6,490
Electricity (1.08 M - 1.79 M kwh)	46,660	77,330
Overhead	28,340	28,340
Property tax, insurance, and administration @ 4%	33,370	35,450
Capital charges @ 0.11746 @ 10%, 20 yrs.	98,000	104,100
Credits - assume negligible credit for recovered product	------	-------
Total Annualized Costs	$287,170	$310,940

CASE B - OUTLINE OF ENGINEERING CALCULATIONS FOR ELECTROSTATIC PRECIPITATOR

Establish overall engineering design as follows:

a. Drift velocity - .21 fps. (average)

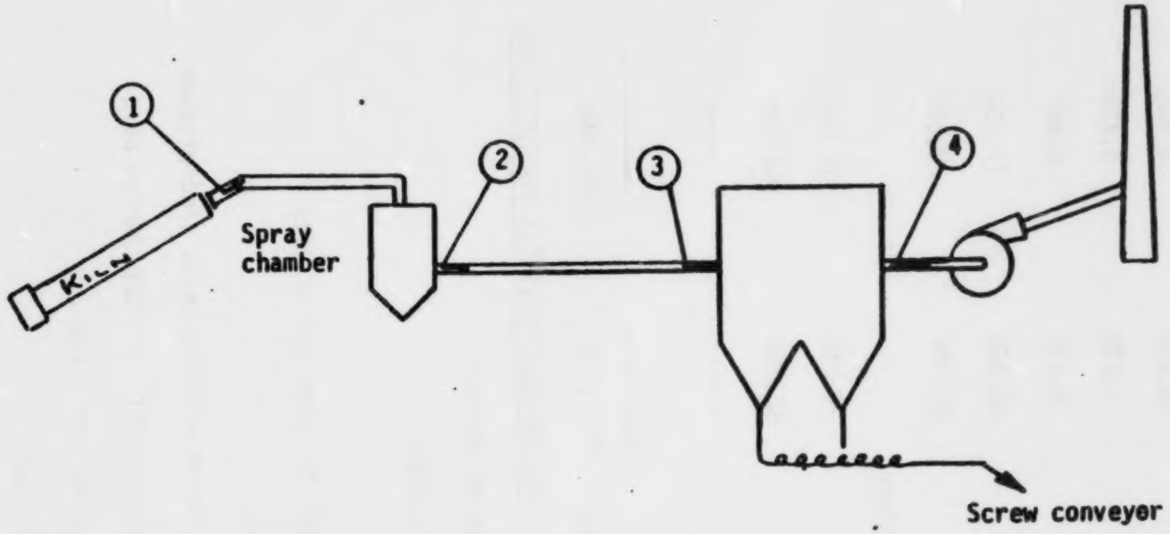
b. Insulated precipitator

c. Inlet gas temperature of 700F for good resistivity

d. Spray chamber next to source

Figure 6-2 shows the system layout for an electrostatic precipitator operation. The following discussion outlines how the design parameters are obtained for each stage along the system.

Stage 1. Same as for Case A, Fabric Filter.


①
Kiln
Spray chamber
②
③
④
Screw conveyer

DESIGN PARAMETER	1	2	3	4
SCFM	30,000	32,770	32,770	32,700
TEMPERATURE	1100 F	800 F	690 F	690 F
ACFM	88,300	77,900	71,100	71,100
DUCT DIAMETER	64"	60"	60"	Neglect
STATIC PRES. (" WG)	Kiln Draft		-1.0"	-1.5"

Figure 6-2 ELECTROSTATIC PRECIPITATOR SYSTEM DESIGN

Stage 2. For preliminary design purposes, assume spray cooling to 800 F with water at 60 F. The water requirements are determined by the change in enthalpy of the gas stream from 1100 F to 800 F divided by the sensible heat gain and latent heat of evaporation per lb of water from 60 F to 800 F. The total water requirement is 129 lbs per min or 15 gpm based on an assumed total pressure of 280 ft including 230 ft for spray nozzles. The added gas volume of 129 lbs per min of water vapor is 2770 scfm. The length of the spray cooler is assumed to be 35 ft. The gas volume after the cooler will be:

$$32770 \text{ SCFM} \times \frac{1260 \text{ R}}{530 \text{ R}} = 77900 \text{ ACFM}$$

Calculate duct diameter:

$$\frac{77900}{4000} \text{ ACFM} = 19.5 \text{ ft}^2$$

Hence 60" duct (19.6 ft^2) may be used.

Stage 3. a. Cooling through the duct is determined again by the method shown in chapter 3 of ref. 88. The length of the duct is 200 ft - 35 ft for the spray cooler or 165 ft. The final temperature is 690 F at the end of the duct and the new gas volume at the precipitator is:

$$77900 \text{ ACFM} \times \frac{1150 \text{ R}}{1260 \text{ R}} = 71100 \text{ ACFM}$$

Two expansion joints will be needed as for baghouses. The pressure drop is assumed to be 0.6" WG for the duct and 0.4" WG for the spray chamber.

b. Size precipitator as follows:

$$A = -71{,}100 \text{ ACFM } \ln(1-.993)/(0.21 \text{ fps} \times 60 \text{ s/min})$$

$$A = 28{,}000 \text{ ft}^2$$

Stage 4. Total pressure drop across system is:

Spray chamber and duct - 1.0" W.G.
Precipitator - .5" W.G.
Total 1.5" W.G.

Size fan for 71,100 ACFM. Select a 50' high stack 57" diameter Fifty feet of screw conveyor 9" in diameter will be required.

COST ESTIMATE OF ELECTROSTATIC PRECIPITATOR SYSTEM

a.	(1) 64" carbon steel elbow, 1/4" thick (Figure 4-10) -	$ 2,200
b.	(1) spray chamber @ 88,300 ACFM (Figure 4-22) -	62,500
c.	(165) feet of 60" carbon steel duct 3/16" thick (Figure 4-7) -	13,500
d.	(2) expansion joints, one 60" and one 64" (Figure 4-12) -	7,800
e.	(1) 28,000 ft^2 precipitator, insulated (Figure 5-2) -	300,000
f.	(1) 71,100 ACFM backwardly curved Class I fan at 1.5" W.G. actual (3.4" standard) (Figure 4-33) -	9,000
g.	(1) 600 RPM, 50 BHP drip-proof motor (Figure 4-34) -	3,000
h.	(1) magnetic starter with circuit breaker (Figure 4-34) -	500
i.	(1) 57" diameter, 50' high stack, 1/4" thick (Figure 4-41) -	5,400
j.	(50) feet of 9" screw conveyor (Figure 4-26) -	3,900
	Total	$407,800

The capital and annualized costs for the electrostatic precipitator system are summarized as follows.

CAPITAL COSTS

Item	Cost
Auxiliary equipment and control device	$407,800
Instruments and controls (10%)	40,800
Taxes and freight (8%)	32,600
Purchased Equipment Costs	$481,200
Direct and indirect installation costs (124% of equipment costs)	596,700
Total Installed Costs	$1,077,900

ANNUALIZED COSTS
(8000 hrs/yr or 1000 shifts)

Item	Costs
Operating labor (0.5 hrs/shift)	$ 4,530
General maintenance (0.5 hr/shift & mat'l)	8,660
Utilities:	
Electricity - fan and pump (280' head for pump)	13,400
precipitator (1.5 watt/sq.ft.)	14,500
Water	1,800
Overhead	7,090
Property tax, insurance and administration @ 4%	43,100
Capital charges @ 0.11746	126,610
Credits - same as Case A	--------
Total Annualized Costs	$ 219,690

CASE C - OUTLINE OF ENGINEERING CALCULATIONS FOR VENTURI SCRUBBERS

Establish overall engineering design as follows:

a. Venturi scrubber pressure drop estimated at 15" W.G.

b. Carbon steel, unlined construction

c. Quencher next to source

Figure 6-3 shows the system layout for a venturi scrubber operation. The following discussion outlines how the design parameters are obtained for each stage along the system.

Stage 1. Same as for Case A, Fabric Filter.

Stage 2. a. The quencher is sized to cool 30,000 scfm gas from 1100 F to 220 F which requires heat transfer of approximately 510,000 Btu/min. The quantity of water required is approximately 55 gpm based on an inlet water temperature of 60 F. Since quenchers are normally supplied excess water, assume a water rate of 60 gpm. The pressure head for the quencher is assumed to be 100 ft (43 psig). The quencher is estimated to be approximately 30 ft long. The new gas volume after the quencher is:

gas: $88{,}300 \text{ ACFM} \times \frac{680 \text{ R}}{1560 \text{ R}} = 38{,}500 \text{ ACFM}$

water vapor: $60 \text{ gpm} \times 8.33 \text{ lb/gas} \times \frac{680 \text{ R}}{530 \text{ R}} \times 21.1 \text{ cu ft/lb}$

$= 13500 \text{ ACFM}$

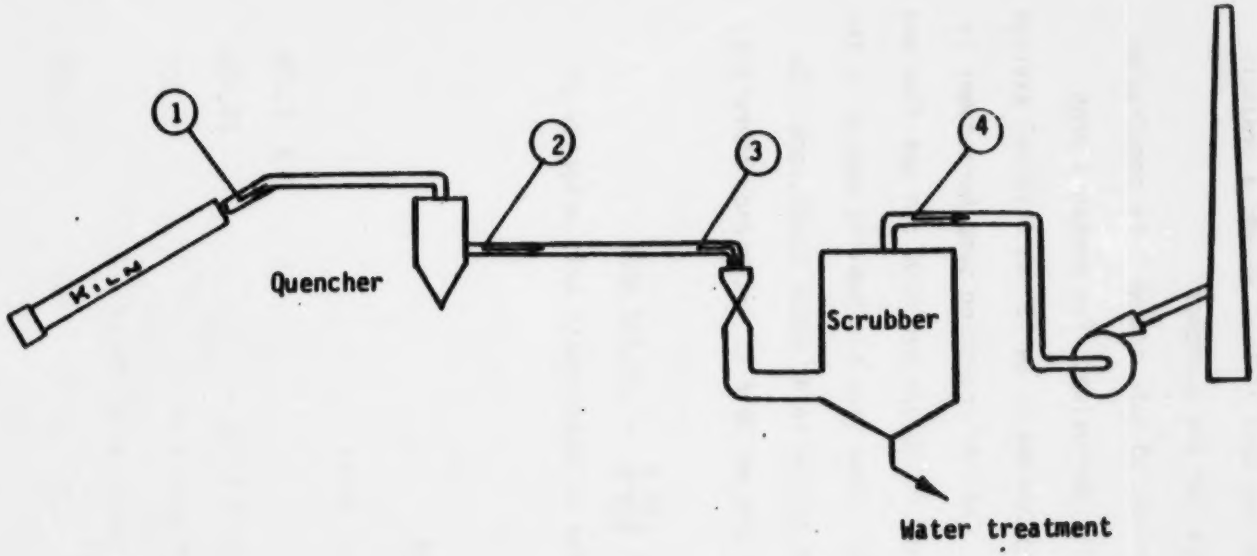
total: $38{,}500 + 13500 = 52{,}000 \text{ ACFM}$

b. Required duct size is:

$$\frac{52{,}000 \text{ ACFM}}{4{,}000 \text{ fpm}} = 13.0 \text{ ft}^2$$

Hence a 48" (12.57 ft^2) duct may be used giving:

$$\frac{52{,}000 \text{ ACFM}}{12.57 \text{ ft}^2} = 4140 \text{ fpm}$$


①
②
③
④
KILN
Quencher
Scrubber
Water treatment

DESIGN PARAMETER	1	2	3	4
SCFM	30,000	40,200	40,200	40,200
TEMPERATURE	1100 F	220 F	190 F	170 F
CFM	88,300	52,000	49,700	48,200
DUCT DIAMETER	64"	48"	48"	Neglect
STATIC PRES. (" WG)	Kiln Draft		-1"	-16"

Figure 6-3 VENTURI SCRUBBER SYSTEM DESIGN

Step 3. Using the heat transfer calculations of ref. 88, the gas temperature will be 190 F after 170 ft of duct. The new gas volume will be:

$$52{,}000 \text{ ACFM} \times \frac{650 \text{ R}}{680 \text{ R}} = 49{,}700 \text{ ACFM}$$

The pressure drop through the duct is 0.6" WG and a pressure drop of 0.4" WG is assumed for the quencher.

Step 4. The scrubber is sized for 49,700 acfm and will be constructed of 3/16" steel to allow for corrosion. The pressure drop through the scrubber is estimated to be 15" WG (typical average for lime kilns, ref 19). The recirculating pump horsepower is estimated to be 20 hp based on 10 gpm per 1000 cfm gas flow and an assumed head of 100 ft. Some sensible cooling occurs in the scrubber and this depends on the inlet water conditions. In this case, a temperature drop of 20 F is estimated; therefore, the fan is sized for:

$$49{,}700 \text{ ACFM} \times \frac{630 \text{ R}}{650 \text{ R}} = 48{,}200 \text{ ACFM}$$

A 48" stack is selected for an approximate exit velocity of 4000 fpm.

COST ESTIMATE OF VENTURI SCRUBBER SYSTEM

a.	(1) 64" carbon steel elbow, 1/4" thick (Figure 4-10) -	$ 2,200
b.	(1) quencher @ 88,300 ACFM (Figure 4-23) -	28,000
c.	(1) quencher pump for 60 gpm (Figure 4-29) -	800
d.	(170) feet of 48" carbon steel duct, 3/16" thick (Figure 4-7) -	11,900

e.	(2) expansion joints, one 48" and one 64" (Figure 4-12) -	7,300.
f.	(1) 49,700 ACFM scrubber, 3/16" thick (Figure 5-4) -	31,200
g.	(1) 48,200 ACFM radial-tip fan at 16" W.G. actual (20" standard) (Figure 4-37). -	10,000
h.	(1) 900 RPM, 225 HP drip-proof motor (Figure 4-34) -	8,000
i.	(1) magnetic starter with circuit breaker (Figure 4-34) -	2,000
j.	(1) 48" diameter, 50' high stack, 1/4" thick (Figure 4-41) -	5,000
	Total	$106,400

The capital and annualized costs for the venturi scrubber system are summarized as follows.

CAPITAL COSTS

Item	Cost
Auxiliary equipment and control device	$106,400
Instruments and controls (10%)	10,640
Taxes and freight (8%)	8,500
Purchased Equipment Costs	$125,540

Item	Cost
Direct and indirect installation costs (91% of equipment costs)	114,240
Total Installed Costs	$239,780

ANNUALIZED COSTS

(8000 hrs/yr or 1000 shifts)

Item	Cost
Operating labor (2 hrs/shift)	$18,100
General maintenance (1 hr/shift + mat'l)	34,640
Utilities:	
Electricity - fan power 1.34 Mkwh	57,890
pump power (100 head)	6,080
Water - 10 gpm/1000 acfm + quencher (at cost of 0.10 $/1000 gal. treated)	26,880
Waste disposal - Cost of waste treatment system is not considered.*	
Overhead	28,340
Property tax, insurance, and administration @ 4%	9,590
Capital charges, 0.16275 @ 10%, 10 yrs.	39,020
Credits	------
Total Annualized Costs	$220,540

SUMMARY OF SYSTEM COSTS FOR THREE METHODS OF CONTROL

Item	Filter	Precipitator	Scrubber
Capital Costs	$ 834,340	$ 1,077,900	$ 239,780
Annualized Costs	$ 287,170	$ 219,690	$ 220,540

---

* The cost of wastewater treatment facilities can be established from ref. 128. Water pollution and treatment are beyond the scope of this manual.

Section 7

UPDATING COSTS TO FUTURE TIME PERIODS

7.1 General

The methods for updating the costs given in this manual are contained in this section. A separate procedure is described for each equipment type or cost item. These procedures have been used to adjust old cost data to December 1977 levels, when necessary, and these procedures are recommended for updating the costs for future time periods. They have been kept as simple as possible. No attempt is made to predict future costs, since this is beyond the scope of this manual. In general, the methods involve use of the Chemical Engineering (CE) plant cost indexes and U.S. Department of Labor, Bureau of Labor Statistics (BLS) wholesale price indexes. Selected index accounts are contained in Appendix B.

These two sets of indexes were selected for applicability, consistency, specificity, and availability. The CE index includes such process industries as (among others):

a. chemicals and petrochemicals
b. fertilizers and agricultural chemicals
c. lime and cement
d. man-made fibers
e. paints, varnishes, pigments, and allied products
f. petroleum refining
g. soap glycerin and related products
h. wood, pulp, paper, and board
i. plastics

These industries are representative of the industries under the attention of this manual. The CE indexes are based on 1957-1959 = 100 and are adjusted for labor productivity changes not found in other cost indexes. Further information is available regarding the make-up of the indexes and it is possible to modify the indexes to suit particular needs (see Arnold, T. H. and Chilton, C. H., New Index Shows Plant Cost Trends, Chemical Engineering, Feb. 18, 1963, pp. 143-149. Also refer to Appendix C, Source Nos. 130 & 131).

Table B-1 gives the CE indexes as far back as 1957. Figure 7-1 shows how the overall CE plant index has changed since its inception. The following are descriptions of the indexes regularly published by Chemical Engineering.

A. ENGINEERING & SUPERVISION

Engineering and Supervision is 10% of the total plant index. It includes the following:

33% Engineers
47% Draftsmen
20% Clerical

B. BUILDINGS.

Buildings is 7% of the total plant index and is based on a special BLS construction index in which the ratio of materials to labor is 53:47.

C. ERECTION & INSTALLATION LABOR

Erection and Installation Labor is 22% of the total plant index. This is the average hourly earning as determined by the BLS for the contract construction industry.

D. EQUIPMENT, MACHINERY, SUPPORTS

Equipment, Machinery and Supports consists of 61% of the total plant index. This index consists of:

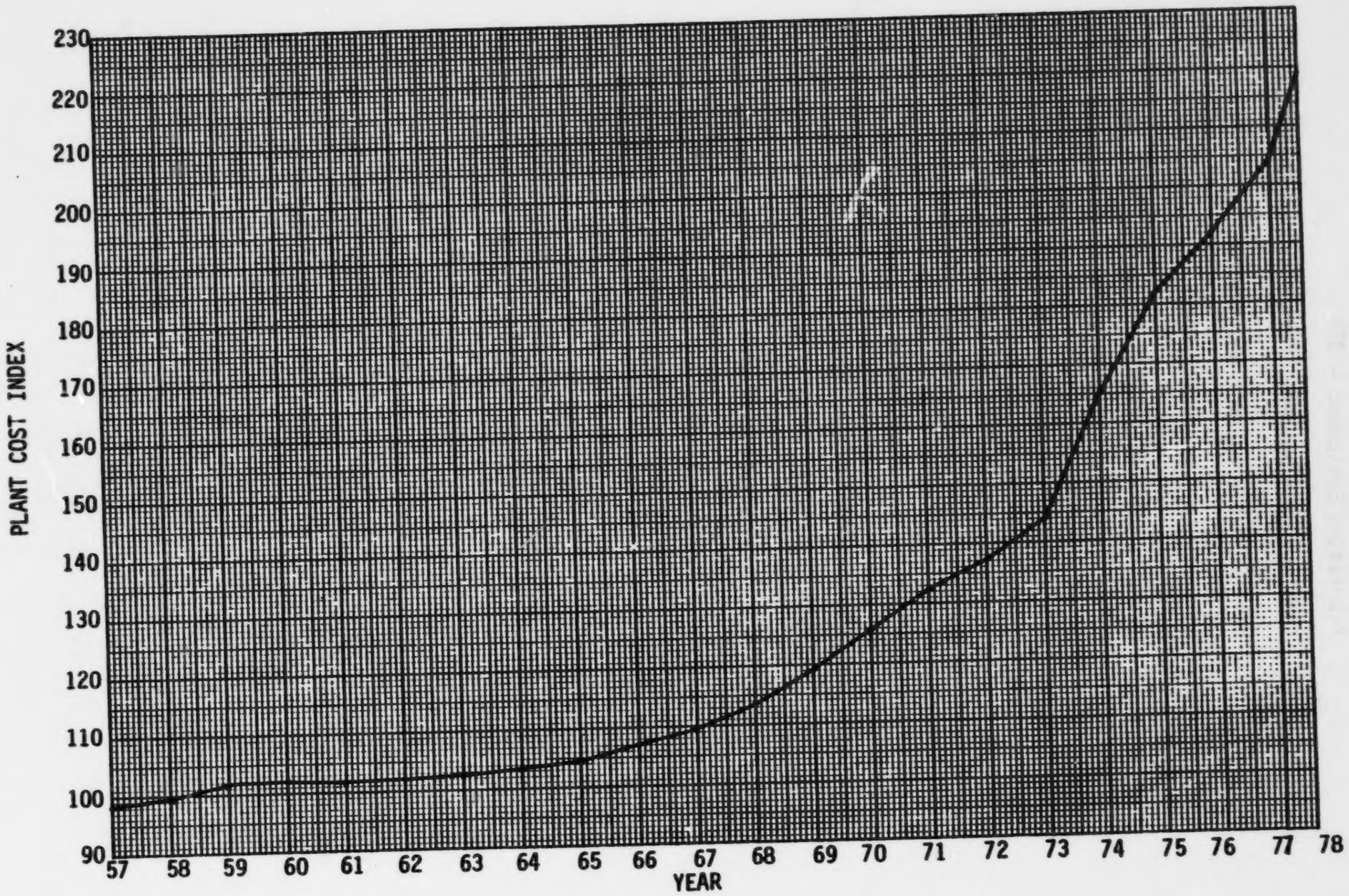


Figure 7-1 CHEMICAL ENGINEERING PLANT COST INDEX

1. Fabricated Equipment - 37%

   Such as:
   - a. boilers, furnaces, and heaters
   - b. columns and towers
   - c. heat exchangers
   - d. condensers and reboilers
   - e. process drums
   - f. reactors
   - g. pressure vessels and tanks
   - h. storage tanks and spheres
   - i. evaporators

2. Process Machinery - 14%

   "Off the shelf" items such as:
   - a. centrifuges
   - b. filters
   - c. mixing and agitating equipment
   - d. rotary kilns and dryers
   - e. conveyors and bucket elevators
   - f. high-pressure vacuum or refrigeration producing equipment
   - g. extruders
   - h. crushing and grinding equipment
   - i. thickeners and settlers
   - j. fans and blowers

3. Pipe, Valves, and Fittings - 20%
4. Process Instruments and Controls - 7%
5. Pumps and Compressors - 7%

6. Electrical Equipment and Materials - 5%

   Such as:
   - a. electric motors
   - b. transformers
   - c. switch gear
   - d. wire and cable

7. Structurals, Supports, Insulation, and Paint - 10%

   Such as:
   - a. structural steel
   - b. foundation materials
   - c. insulation
   - d. lumber
   - e. paint

Cost elements not included in the CE indexes include:

a. site clearing and preparation
b. insurance and taxes during construction
c. company overhead allocated to the project
d. contractor's overhead

For purposes of this manual, the CE indexes have been used whenever there is no specifically applicable BLS wholesale price index. The BLS indexes used are given in Tables B-2 thru B-20; the specific commodities and associated BLS code number and year of reference are listed below:

Code No.	Base Year=100	Commodity	Table No.
0312	1967	Cotton Broadwoven Goods	B-2
0334	1967	Manmade Fiber Broadwoven Goods	B-3
05310101	1967	Natural Gas	B-21
0543	Dec/1970	Industrial Power	B-22
07	1967	Rubber and Plastic Products	B-4
10130246	1967	A-36, Carbon Steel Plates	B-5

Code No.	Base Year=100	Commodity	Table No.
10130247	1967	Stainless Steel Plate	B-6
10130262	1967	Carbon Steel Sheet	B-7
10130264	1967	Stainless Steel Sheet	B-8
1141	1967	Pumps, Compressors, and Equipment	B-9
11450133	1967	V-Belt Sheaves	B-10
1147	1967	Fans and Blowers, Except Portable	B-11
11730112	1967	10 HP, AC Motors	B-12
11730113	1967	250 HP, AC Motors	B-13
11730119	1967	50 HP, AC Motors	B-14
11750781	1967	75 HP, 440 volt, AC Starters	B-15
135	1967	Refractories	B-16
13520111	1967	Fire Clay Brick, Super Duty	B-17
13520131	1967	High Alumina Brick, 70 Pct.	B-18
13520151	Dec/1974	Castable Refractories	B-19
1392	1967	Insulation Materials	B-20

7.2 Equipment Cost Updating Procedures

Using these indexes, the procedures for updating the purchase costs of each equipment type will now be discussed.

Electrostatic Precipitators

Use CE Fabricated Equipment index. For precipitators with insulation, use the following composite index on the additional cost only:

1/2 (BLS #1392 factor) + (CE Fabricated Equipment Factor).

Venturi Scrubbers

Use CE Fabricated Equipment index. For rubber liners use BLS #07 on the liner cost only.

Fabric Filters

Use CE Fabricated Equipment index. For filters with insulation, use same procedure as for precipitators with insulation. For stainless steel construction, use BLS #10130264 on the additional cost. For filter media use BLS #0312 or #0334.

Thermal and Catalytic Incinerators

Use CE Fabricated Equipment index for custom units. Use CE Process Equipment index for package units.

Adsorbers

Same as for thermal and catalytic incinerators.

Absorbers

Use CE Fabricated Equipment index

Refrigeration

Use CE Process Equipment index

Flares

Use CE Fabricated Equipment index

Ductwork

Use CE Fabricated Equipment index. For refractories, however, use the appropriate BLS index; the base index is #135.

Dampers

Use CE Fabricated Equipment index. For automatic dampers, use CE Process Instruments and Controls on that portion of price attributable to automatic control.

Heat Exchangers

Use CE Fabricated Equipment index.

Mechanical Collectors

Use CE Process Machinery index.

Fans, Motors, and Starters

For fans use BLS #1147. For motors use the appropriate BLS index; the base index is #1173. For starters use BLS #11750781. For V-belts use BLS #11450133.

Stacks

Use CE Fabricated Equipment index.

Cooling Tower

Use CE Fabricated Equipment index.

Pumps

Use BLS #1141 index.

Dust Removal Equipment

For screw conveyors, use the CE Fabricated Equipment index. For water treatment equipment, use the appropriate CE or BLS index, depending on the equipment component.

APPENDIX A

COMPOUND INTEREST FACTORS

Table A-1 1% COMPOUND INTEREST FACTORS

	Single Payment	Uniform Series	
n	Present Worth Factor P/F	Capital Recovery Factor A/P	Present Worth Factor P/A
1	0.9901	1.01000	0.990
2	0.9803	0.50751	1.970
3	0.9706	0.34002	2.941
4	0.9610	0.25628	3.902
5	0.9515	0.20604	4.853
6	0.9420	0.17255	5.795
7	0.9327	0.14863	6.728
8	0.9235	0.13069	7.652
9	0.9143	0.11674	8.566
10	0.9053	0.10558	9.471
11	0.8963	0.09645	10.368
12	0.8874	0.08885	11.255
13	0.8787	0.08241	12.134
14	0.8700	0.07690	13.004
15	0.8613	0.07212	13.865
16	0.8528	0.06794	14.718
17	0.8444	0.06426	15.562
18	0.8360	0.06098	16.398
19	0.8277	0.05805	17.226
20	0.8195	0.05542	18.046
21	0.8114	0.05303	18.857
22	0.8034	0.05086	19.660
23	0.7954	0.04889	20.456
24	0.7876	0.04707	21.243
25	0.7798	0.04541	22.023
26	0.7720	0.04387	22.795
27	0.7644	0.04245	23.560
28	0.7568	0.04112	24.316
29	0.7493	0.03990	25.066
30	0.7419	0.03875	25.808
31	0.7346	0.03768	26.542
32	0.7273	0.03667	27.270
33	0.7201	0.03573	27.990
34	0.7130	0.03484	28.703
35	0.7059	0.03400	29.409
40	0.6717	0.03046	32.835
45	0.6391	0.02771	36.095
50	0.6080	0.02551	39.196

Table A-2 2% COMPOUND INTEREST FACTORS

	Single Payment	Uniform Series	
n	Present Worth Factor P/F	Capital Recovery Factor A/P	Present Worth Factor P/A
1	0.9804	1.02000	0.980
2	0.9612	0.51505	1.942
3	0.9423	0.34675	2.884
4	0.9238	0.26262	3.808
5	0.9057	0.21216	4.713
6	0.8880	0.17853	5.601
7	0.8/06	0.15451	6.472
8	0.8535	0.13651	7.325
9	0.8368	0.12252	8.162
10	0.8203	0.11133	8.983
11	0.8043	0.10218	9.787
12	0.7885	0.09456	10.575
13	0.7730	0.08812	11.348
14	0.7579	0.08260	12.106
15	0.7430	0.07783	12.849
16	0.7284	0.07365	13.578
17	0.7142	0.06997	14.292
18	0.7002	0.06670	14.992
19	0.6864	0.06378	15.678
20	0.6730	0.06116	16.351
21	0.6598	0.05878	17.011
22	0.6468	0.05663	17.658
23	0.6342	0.05467	18.292
24	0.6217	0.05287	18.914
25	0.6095	0.05122	19.523
26	0.5976	0.04970	20.121
27	0.5859	0.04829	20.707
28	0.5744	0.04699	21.281
29	0.5631	0.04578	21.844
30	0.5521	0.04465	22.396
31	0.5412	0.04360	22.938
32	0.5306	0.04261	23.468
33	0.5202	0.04169	23.989
34	0.5100	0.04082	24.499
35	0.5000	0.04000	24.999
40	0.4529	0.03656	27.355
45	0.4102	0.03391	29.490
50	0.3715	0.03182	31.424

Table A-3 3% COMPOUND INTEREST FACTORS

	Single Payment	Uniform Series	
n	Present Worth Factor P/F	Capital Recovery Factor A/P	Present Worth Factor P/A
1	0.9709	1.03000	0.971
2	0.9426	0.52261	1.913
3	0.9151	0.35353	2.829
4	0.8885	0.26903	3.717
5	0.8626	0.21835	4.580
6	0.8375	0.18460	5.417
7	0.8131	0.16051	6.230
8	0.7894	0.14246	7.020
9	0.7664	0.12843	7.786
10	0.7441	0.11723	8.530
11	0.7224	0.10808	9.253
12	0.7014	0.10046	9.954
13	0.6810	0.09403	10.635
14	0.6611	0.08853	11.296
15	0.6419	0.08377	11.938
16	0.6232	0.07961	12.561
17	0.6050	0.07595	13.166
18	0.5874	0.07271	13.754
19	0.5703	0.06981	14.324
20	0.5537	0.06722	14.877
21	0.5375	0.06487	15.415
22	0.5219	0.06275	15.937
23	0.5067	0.06081	16.444
24	0.4919	0.05905	16.936
25	0.4776	0.05743	17.413
26	0.4637	0.05594	17.877
27	0.4502	0.05456	18.327
28	0.4371	0.05329	18.764
29	0.4243	0.05211	19.188
30	0.4120	0.05102	19.600
31	0.4000	0.05000	20.000
32	0.3883	0.04905	20.389
33	0.3770	0.04816	20.766
34	0.3660	0.04732	21.132
35	0.3554	0.04654	21.487
40	0.3066	0.04326	23.115
45	0.2644	0.04079	24.519
50	0.2281	0.03887	25.730

Table A-4 4% COMPOUND INTEREST FACTORS

	Single Payment	Uniform Series	
n	Present Worth Factor P/F	Capital Recovery Factor A/P	Present Worth Factor P/A
1	0.9615	1.04000	0.962
2	0.9246	0.53020	1.886
3	0.8890	0.36035	2.775
4	0.8548	0.27549	3.630
5	0.8219	0.22463	4.452
6	0.7903	0.19076	5.242
7	0.7599	0.16661	6.002
8	0.7307	0.14853	6.733
9	0.7026	0.13449	7.435
10	0.6756	0.12329	8.111
11	0.6496	0.11415	8.760
12	0.6246	0.10655	9.385
13	0.6006	0.10014	9.986
14	0.5775	0.09467	10.563
15	0.5553	0.08994	11.118
16	0.5339	0.08582	11.652
17	0.5134	0.08220	12.166
18	0.4936	0.07899	12.659
19	0.4746	0.07614	13.134
20	0.4564	0.07358	13.590
21	0.4388	0.07128	14.029
22	0.4220	0.06920	14.451
23	0.4057	0.06731	14.857
24	0.3901	0.06559	15.247
25	0.3751	0.06401	15.622
26	0.3607	0.06257	15.983
27	0.3468	0.06124	16.330
28	0.3335	0.06001	16.663
29	0.3207	0.05888	16.984
30	0.3083	0.05783	17.292
31	0.2965	0.05686	17.588
32	0.2851	0.05595	17.874
33	0.2741	0.05510	18.148
34	0.2636	0.05431	18.411
35	0.2534	0.05358	18.665
40	0.2083	0.05052	19.793
45	0.1712	0.04826	20.720
50	0.1407	0.04655	21.482

Table A-5 5% COMPOUND INTEREST FACTORS

	Single Payment	Uniform Series	
n	Present Worth Factor P/F	Capital Recovery Factor A/P	Present Worth Factor P/A
1	0.9524	1.05000	0.952
2	0.9070	0.53780	1.859
3	0.8638	0.36721	2.723
4	0.8227	0.28201	3.546
5	0.7835	0.23097	4.329
6	0.7462	0.19702	5.076
7	0.7107	0.17282	5.786
8	0.6768	0.15472	6.463
9	0.6446	0.14069	7.108
10	0.6139	0.12950	7.722
11	0.5847	0.12039	8.306
12	0.5568	0.11283	8.863
13	0.5303	0.10646	9.394
14	0.5051	0.10102	9.899
15	0.4810	0.09634	10.380
16	0.4581	0.09227	10.838
17	0.4363	0.08870	11.274
18	0.4155	0.08555	11.690
19	0.3957	0.08275	12.085
20	0.3769	0.08024	12.462
21	0.3589	0.07800	12.821
22	0.3418	0.07597	13.163
23	0.3256	0.07414	13.489
24	0.3101	0.07247	13.799
25	0.2953	0.07095	14.094
26	0.2812	0.06956	14.375
27	0.2678	0.06829	14.643
28	0.2551	0.06712	14.898
29	0.2429	0.06605	15.141
30	0.2314	0.06505	15.372
31	0.2204	0.06413	15.593
32	0.2099	0.06328	15.803
33	0.1999	0.06249	16.003
34	0.1904	0.06176	16.193
35	0.1813	0.06107	16.374
40	0.1420	0.05828	17.159
45	0.1113	0.05626	17.774
50	0.0872	0.05478	18.256

Table A-6 6% COMPOUND INTEREST FACTORS

	Single Payment	**Uniform Series**	
n	Present Worth Factor P/F	Capital Recovery Factor A/P	Present Worth Factor P/A
1	0.9434	1.06000	0.943
2	0.8900	0.54544	1.833
3	0.8396	0.37411	2.673
4	0.7921	0.28859	3.465
5	0.7473	0.23740	4.212
6	0.7050	0.20336	4.917
7	0.6651	0.17914	5.582
8	0.6274	0.16104	6.210
9	0.5919	0.14702	6.802
10	0.5584	0.13587	7.360
11	0.5268	0.12679	7.887
12	0.4970	0.11928	8.384
13	0.4688	0.11296	8.853
14	0.4423	0.10758	9.295
15	0.4173	0.10296	9.712
16	0.3936	0.09895	10.106
17	0.3714	0.09544	10.477
18	0.3503	0.09236	10.828
19	0.3305	0.08962	11.158
20	0.3118	0.08718	11.470
21	0.2942	0.08500	11.764
22	0.2775	0.08305	12.042
23	0.2618	0.08128	12.303
24	0.2470	0.07968	12.550
25	0.2330	0.07823	12.783
26	0.2198	0.07690	13.003
27	0.2074	0.07570	13.211
28	0.1956	0.07459	13.406
29	0.1846	0.07358	13.591
30	0.1741	0.07265	13.765
31	0.1643	0.07179	13.929
32	0.1550	0.07100	14.084
33	0.1462	0.07027	14.230
34	0.1379	0.06960	14.368
35	0.1301	0.06897	14.498
40	0.0972	0.06646	15.046
45	0.0727	0.06470	15.456
50	0.0543	0.06344	15.762

Table A-7 7% COMPOUND INTEREST FACTORS

	Single Payment	Uniform Series	
n	Present Worth Factor P/F	Capital Recovery Factor A/P	Present Worth Factor P/A
1	0.9346	1.07000	0.935
2	0.8734	0.55309	1.808
3	0.8163	0.38105	2.624
4	0.7629	0.29523	3.387
5	0.7130	0.24389	4.100
6	0.6663	0.20980	4.767
7	0.6227	0.18555	5.389
8	0.5820	0.16747	5.971
9	0.5439	0.15349	6.515
10	0.5083	0.14238	7.024
11	0.4751	0.13336	7.499
12	0.4440	0.12590	7.943
13	0.4150	0.11965	8.358
14	0.3878	0.11434	8.745
15	0.3624	0.10979	9.108
16	0.3387	0.10586	9.447
17	0.3166	0.10243	9.763
18	0.2959	0.09941	10.059
19	0.2765	0.09675	10.336
20	0.2584	0.09439	10.594
21	0.2415	0.09229	10.836
22	0.2257	0.09041	11.061
23	0.2109	0.08871	11.272
24	0.1971	0.08719	11.469
25	0.1842	0.08581	11.654
26	0.1722	0.08456	11.826
27	0.1609	0.08343	11.987
28	0.1504	0.08239	12.137
29	0.1406	0.08145	12.278
30	0.1314	0.08059	12.409
31	0.1228	0.07980	12.532
32	0.1147	0.07907	12.647
33	0.1072	0.07841	12.754
34	0.1002	0.07780	12.854
35	0.0937	0.07723	12.948
40	0.0668	0.07501	13.332
45	0.0476	0.07350	13.606
50	0.0339	0.07246	13.801

Table A-8 8% COMPOUND INTEREST FACTORS

	Single Payment	Uniform Series	
n	Present Worth Factor P/F	Capital Recovery Factor A/P	Present Worth Factor P/A
1	0.9259	1.08000	0.926
2	0.8573	0.56077	1.783
3	0.7938	0.38803	2.577
4	0.7350	0.30192	3.312
5	0.6806	0.25046	3.993
6	0.6302	0.21632	4.623
7	0.5835	0.19207	5.206
8	0.5403	0.17401	5.747
9	0.5002	0.16008	6.247
10	0.4632	0.14903	6.710
11	0.4289	0.14008	7.139
12	0.3971	0.13270	7.536
13	0.3677	0.12652	7.904
14	0.3405	0.12130	8.244
15	0.3152	0.11683	8.559
16	0.2919	0.11298	8.851
17	0.2703	0.10963	9.122
18	0.2502	0.10670	9.372
19	0.2317	0.10413	9.604
20	0.2145	0.10185	9.818
21	0.1987	0.09983	10.017
22	0.1839	0.09803	10.201
23	0.1703	0.09642	10.371
24	0.1577	0.09498	10.529
25	0.1460	0.09368	10.675
26	0.1352	0.09251	10.810
27	0.1252	0.09145	10.935
28	0.1159	0.09049	11.051
29	0.1073	0.08962	11.158
30	0.0994	0.08883	11.258
31	0.0920	0.08811	11.350
32	0.0852	0.08745	11.435
33	0.0789	0.08685	11.514
34	0.0730	0.08630	11.587
35	0.0676	0.08580	11.655
40	0.0460	0.08386	11.925
45	0.0313	0.08259	12.108
50	0.0213	0.08174	12.233

Table A-9 10% COMPOUND INTEREST FACTORS

	Single Payment	Uniform Series	
n	Present Worth Factor P/F	Capital Recovery Factor A/P	Present Worth Factor P/A
1	0.9091	1.10000	0.909
2	0.8264	0.57619	1.736
3	0.7513	0.40211	2.487
4	0.6830	0.31547	3.170
5	0.6209	0.26380	3.791
6	0.5645	0.22961	4.355
7	0.5132	0.20541	4.868
8	0.4665	0.18744	5.355
9	0.4241	0.17364	5.759
10	0.3855	0.16275	6.144
11	0.3505	0.15396	6.495
12	0.3186	0.14676	6.814
13	0.2897	0.14078	7.103
14	0.2633	0.13575	7.367
15	0.2394	0.13147	7.606
16	0.2176	0.12782	7.824
17	0.1978	0.12466	8.022
18	0.1799	0.12193	8.201
19	0.1635	0.11955	8.365
20	0.1486	0.11746	8.514
21	0.1351	0.11562	8.649
22	0.1228	0.11401	8.772
23	0.1117	0.11257	8.883
24	0.1015	0.11130	8.985
25	0.0923	0.11017	9.077
26	0.0839	0.10916	9.161
27	0.0763	0.10826	9.237
28	0.0693	0.10745	9.307
29	0.0630	0.10673	9.370
30	0.0573	0.10608	9.427
31	0.0521	0.10550	9.479
32	0.0474	0.10497	9.526
33	0.0431	0.10450	9.569
34	0.0391	0.10407	9.609
35	0.0356	0.10369	9.644
40	0.0221	0.10226	9.779
45	0.0137	0.10139	9.863
50	0.0085	0.10086	9.915

Table A-10 12% COMPOUND INTEREST FACTORS

	Single Payment	Uniform Series	
n	Present Worth Factor P/F	Capital Recovery Factor A/P	Present Worth Factor P/A
1	0.8929	1.12000	0.893
2	0.7972	0.59170	1.690
3	0.7118	0.41635	2.402
4	0.6355	0.32923	3.037
5	0.5674	0.27741	3.605
6	0.5066	0.24323	4.111
7	0.4523	0.21912	4.564
8	0.4039	0.20130	4.968
9	0.3606	0.18768	5.328
10	0.3220	0.17698	5.650
11	0.2875	0.16842	5.938
12	0.2567	0.16144	6.194
13	0.2292	0.15568	6.424
14	0.2046	0.15087	6.628
15	0.1827	0.14682	6.811
16	0.1631	0.14339	6.974
17	0.1456	0.14046	7.120
18	0.1300	0.13794	7.250
19	0.1161	0.13576	7.366
20	0.1037	0.13388	7.469
21	0.0926	0.13224	7.562
22	0.0826	0.13081	7.645
23	0.0738	0.12956	7.718
24	0.0659	0.12846	7.784
25	0.0588	0.12750	7.843
26	0.0525	0.12665	7.896
27	0.0469	0.12590	7.943
28	0.0419	0.12524	7.984
29	0.0374	0.12466	8.022
30	0.0334	0.12414	8.055
31	0.0298	0.12369	8.085
32	0.0266	0.12328	8.112
33	0.0238	0.12292	8.135
34	0.0212	0.12260	8.157
35	0.0189	0.12232	8.176
40	0.0107	0.12130	8.244
45	0.0061	0.12074	8.283
50	0.0035	0.12042	8.305

Table A-11 15% COMPOUND INTEREST FACTORS

	Single Payment	Uniform Series	
n	Present Worth Factor P/F	Capital Recovery Factor A/P	Present Worth Factor P/A
1	0.8696	1.15000	0.870
2	0.7561	0.61512	1.626
3	0.6575	0.43798	2.283
4	0.5718	0.35027	2.855
5	0.4972	0.29832	3.352
6	0.4323	0.26424	3.784
7	0.3759	0.24036	4.160
8	0.3269	0.22285	4.487
9	0.2843	0.20957	4.772
10	0.2472	0.19925	5.019
11	0.2149	0.19107	5.234
12	0.1869	0.18448	5.421
13	0.1625	0.17911	5.583
14	0.1413	0.17469	5.724
15	0.1229	0.17102	5.847
16	0.1069	0.16795	5.954
17	0.0929	0.16537	6.047
18	0.0808	0.16319	6.128
19	0.0703	0.16134	6.198
20	0.0611	0.15976	6.259
21	0.0531	0.15842	6.312
22	0.0462	0.15727	6.359
23	0.0402	0.15628	6.399
24	0.0349	0.15543	6.434
25	0.0304	0.15470	6.464
26	0.0264	0.15407	6.491
27	0.0230	0.15353	6.514
28	0.0200	0.15306	6.534
29	0.0174	0.15265	6.551
30	0.0151	0.15230	6.566
31	0.0131	0.15200	6.579
32	0.0114	0.15173	6.591
33	0.0099	0.15150	6.600
34	0.0086	0.15131	6.609
35	0.0075	0.15113	6.617
40	0.0037	0.15056	6.642
45	0.0019	0.15028	6.654
50	0.0009	0.15014	6.661

Table A-12 20% COMPOUND INTEREST FACTORS

	Single Payment	Uniform Series	
n	Present Worth Factor P/F	Capital Recovery Factor A/P	Present Worth Factor P/A
1	0.8333	1.20000	0.833
2	0.6944	0.65455	1.528
3	0.5787	0.47473	2.106
4	0.4823	0.38629	2.589
5	0.4019	0.33438	2.991
6	0.3349	0.30071	3.326
7	0.2791	0.27742	3.605
8	0.2326	0.26061	3.837
9	0.1938	0.24808	4.031
10	0.1615	0.23852	4.192
11	0.1346	0.23110	4.327
12	0.1122	0.22526	4.439
13	0.0935	0.22062	4.533
14	0.0779	0.21689	4.611
15	0.0649	0.21388	4.675
16	0.0541	0.21144	4.730
17	0.0451	0.20944	4.775
18	0.0376	0.20781	4.812
19	0.0313	0.20646	4.844
20	0.0261	0.20536	4.870
21	0.0217	0.20444	4.891
22	0.0181	0.20369	4.909
23	0.0151	0.20307	4.925
24	0.0126	0.20255	4.937
25	0.0105	0.20212	4.948
26	0.0087	0.20176	4.956
27	0.0073	0.20147	4.964
28	0.0061	0.20122	4.970
29	0.0051	0.20102	4.975
30	0.0042	0.20085	4.979
31	0.0035	0.20070	4.982
32	0.0029	0.20059	4.985
33	0.0024	0.20049	4.988
34	0.0020	0.20041	4.990
35	0.0017	0.20034	4.992
40	0.0007	0.20014	4.997
45	0.0003	0.20005	4.999
50	0.0001	0.20002	4.999

APPENDIX B

EQUIPMENT COST INDEXES

TABLE B-1 CHEMICAL ENGINEERING PLANT COST INDEXES

INDEX	1978 ANNUAL	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
CE Plant Index	218.8	210.6	213.1	214.1	215.7	216.9	217.7	219.2	221.6	222.8	223.5	224.7	225.9
Engineering & Supervision	161.9	159.2	159.6	159.9	160.3	160.6	161.0	161.6	162.0	162.3	162.6	165.4	168.2
Building	213.7	207.0	210.5	210.3	211.1	212.8	214.0	215.0	214.3	216.3	217.2	217.8	218.1
Construction Labor	185.8	182.8	181.1	182.0	180.7	183.1	183.4	186.6	188.2	191.0	190.8	190.3	190.5
Equipment, Machinery Supports	240.6	229.6	233.8	234.9	237.9	238.8	239.8	240.9	244.2	244.9	246.0	247.6	249.0
Fabricated Equipment	238.6	226.6	233.0	233.6	237.1	237.3	237.4	238.6	243.3	243.2	243.8	244.1	245.2
Process Machinery	228.3	218.1	221.6	222.7	224.3	225.5	226.8	228.6	231.0	232.5	234.1	235.8	237.8
Pipe, Valves & Fittings	269.4	256.0	262.2	264.0	266.0	267.0	268.4	269.1	273.1	274.9	276.5	278.1	277.9
Process Instruments & Controls	216.0	209.8	211.0	211.0	212.1	214.2	214.6	217.2	218.3	218.6	219.5	221.7	223.7
Pumps & Compressors	257.5	248.4	250.3	250.6	254.2	256.3	258.2	258.6	258.8	259.1	260.9	266.6	268.1
Electrical Equipment & Materials	167.8	162.5	162.9	162.8	164.6	166.4	167.9	168.7	169.5	170.0	170.5	173.5	174.1
Structural Supports Insulation & Paint	249.1	235.5	236.8	240.7	246.6	247.4	250.1	250.5	253.6	254.7	256.1	258.0	258.7

SOURCE: _Chemical Engineering_, Economic Indicators

Table B-1 CHEMICAL ENGINEERING PLANT COST INDEXES

INDEX	1977 ANNUAL	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
CE Plant Index	204.1	198.7	198.5	199.3	200.3	201.4	202.3	204.7	206.4	208.8	209.0	209.4	210.3
Engineering & Supervision	162.1	158.3	159.0	159.7	160.4	161.0	161.7	162.4	163.1	163.8	164.4	165.1	165.8
Building	199.1	194.0	193.6	195.3	196.7	197.3	197.2	199.0	201.0	204.2	203.6	203.5	204.1
Construction Labor	178.2	178.5	176.3	175.7	175.6	175.9	176.8	177.1	178.1	180.8	181.5	180.9	181.2
Equipment, Machinery Supports	220.9	213.2	213.6	214.8	216.2	217.7	218.8	222.3	224.3	226.8	226.9	227.7	228.7
Fabricated Equipment	216.6	208.3	208.3	208.9	210.2	211.9	212.8	219.8	222.1	223.9	222.9	224.4	226.2
Process Machinery	211.6	205.8	206.1	207.1	207.8	209.0	210.1	212.3	213.8	215.0	216.0	217.4	218.3
Pipe, Valves & Fittings	247.7	236.3	238.1	241.0	244.6	246.5	247.3	248.2	251.9	254.1	255.0	254.1	254.9
Process Instruments & Controls	203.3	199.5	199.6	200.1	200.8	201.5	201.5	202.5	203.1	204.3	207.8	209.1	209.9
Pumps & Compressors	240.2	234.6	234.3	234.4	234.4	237.2	238.8	241.8	241.9	244.0	245.4	247.9	248.0
Electrical Equipment & Materials	159.0	154.0	154.9	156.4	157.2	158.0	159.2	160.6	160.3	161.3	161.8	161.9	162.4
Structural Supports Insulation & Paint	226.0	219.3	219.2	220.7	221.3	221.7	223.6	225.2	226.2	235.4	233.2	233.0	233.5

SOURCE: Chemical Engineering, Economic Indicators

Table B-1 CHEMICAL ENGINEERING PLANT COST INDEXES

INDEX	1976 ANNUAL	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
CE Plant Index	192.1	187.3	187.5	188.4	188.9	190.2	191.1	192.0	193.9	195.6	196.3	196.4	197.4
Engineering & Supervision	150.8	147.9	148.5	149.1	149.6	150.2	150.7	151.2	151.7	152.1	152.6	153.0	153.5
Building	187.4	182.6	182.9	184.4	185.2	186.0	185.3	186.5	188.3	190.8	191.4	192.0	192.9
Construction Labor	174.2	172.8	171.3	172.5	171.3	173.4	172.9	174.3	174.6	176.5	177.1	176.9	177.0
Equipment, Machinery Supports	205.8	199.5	200.3	200.9	202.1	203.3	205.0	205.6	208.5	210.2	211.0	211.0	212.5
Fabricated Equipment	200.8	196.2	196.3	196.6	196.0	197.0	198.5	198.9	203.7	205.3	205.9	206.5	208.3
Process Machinery	197.5	191.6	192.9	193.1	193.8	194.9	196.9	198.0	199.0	200.7	201.7	202.8	204.5
Pipe, Valves & Fittings	232.5	222.9	223.0	223.9	229.0	231.9	235.1	235.8	236.9	238.0	239.1	236.8	237.3
Process Instruments & Controls	193.1	188.2	189.6	190.0	190.4	191.3	192.5	193.2	193.3	195.3	197.1	197.5	198.7
Pumps & Compressors	220.9	211.5	217.7	218.0	219.5	219.4	221.2	221.3	222.6	223.9	223.2	223.7	228.7
Electrical Equipment & Materials	148.9	145.0	145.6	146.1	146.9	147.3	147.6	147.6	148.9	150.6	153.8	153.9	153.4
Structural Supports Insulation & Paint	209.7	202.6	202.3	204.9	205.5	206.5	206.7	207.5	213.3	216.8	216.8	216.4	217.0

SOURCE: Chemical Engineering, Economic Indicators

Table B-1 CHEMICAL ENGINEERING PLANT COST INDEXES

INDEX	1975 ANNUAL	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
CE Plant Index	182.3	179.4	179.5	180.7	180.7	180.8	181.8	182.1	181.9	183.7	185.6	185.5	186.2
Engineering & Supervision	141.8	139.6	139.8	140.2	140.7	141.1	141.6	142.0	142.4	142.9	143.3	143.7	144.2
Building	176.9	173.1	173.6	174.7	175.5	175.8	176.3	177.1	177.5	178.8	180.2	179.4	181.1
Construction Labor	168.4	166.7	164.2	167.4	166.6	165.5	167.3	168.4	168.7	171.9	172.0	171.2	171.1
Equipment, Machinery Supports	194.7	191.6	192.3	192.9	193.0	193.3	194.3	194.2	193.7	195.2	198.1	198.2	199.1
Fabricated Equipment	192.2	190.7	190.6	191.6	191.6	191.1	191.5	190.0	190.0	191.4	195.8	195.2	196.4
Process Machinery	184.7	179.1	179.9	181.4	182.5	182.8	184.7	185.5	185.1	186.3	188.8	189.6	190.9
Pipe, Valves & Fittings	217.0	209.8	212.9	212.8	213.5	217.2	217.8	216.0	216.7	219.9	221.6	222.6	223.3
Process Instruments & Controls	181.4	177.6	177.8	177.7	178.8	178.9	180.4	180.2	181.2	183.3	186.3	186.6	187.8
Pumps & Compressors	208.3	208.7	208.7	208.7	206.2	206.2	208.3	209.1	207.6	209.4	209.1	209.1	209.0
Electrical Equipment & Materials	143.0	141.5	141.7	142.4	141.4	141.8	142.0	151.5	141.6	141.8	143.1	143.7	143.3
Structural Supports Insulation & Paint	198.6	198.6	198.2	198.4	198.0	195.5	196.4	198.5	198.5	197.9	200.7	200.7	201.2

SOURCE: Chemical Engineering, Economic Indicators

Table B-1 CHEMICAL ENGINEERING PLANT COST INDEXES (cont'd)

INDEX	1974 ANNUAL	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
CE Plant Index	165.4	150.0	150.7	153.8	156.7	161.4	164.7	168.8	172.2	174.8	176.0	177.4	177.8
Engineering & Supervision	134.4	131.6	131.9	132.2	132.5	132.8	132.8	134.0	134.3	134.5	138.2	138.7	139.1
Building	165.5	156.7	156.4	158.8	162.3	164.3	165.4	167.1	170.6	172.7	170.5	172.1	172.5
Construction Labor	163.4	162.7	162.4	162.3	162.7	160.0	159.4	159.5	164.1	166.6	165.8	166.9	166.5
Equipment, Machinery Supports	171.2	147.7	149.0	153.7	157.8	166.2	171.8	178.0	181.6	184.7	186.5	188.1	188.8
Fabricated Equipment	170.1	147.3	148.7	152.7	155.1	165.1	169.3	179.0	181.4	184.0	186.0	186.1	186.8
Process Machinery	160.3	143.1	143.7	146.8	149.4	154.8	159.2	163.5	167.9	170.3	172.9	175.7	177.2
Pipe, Valves & Fittings	192.2	162.6	163.2	169.9	179.6	189.6	197.1	203.0	206.7	209.4	209.7	208.3	208.7
Process Instruments & Controls	164.7	152.0	153.4	158.2	157.2	159.7	162.7	165.8	168.2	173.2	174.1	175.2	176.9
Pumps & Compressors	175.7	144.0	145.8	150.6	157.9	168.2	175.6	182.7	186.8	187.3	195.8	206.9	206.9
Electrical Equipment & Materials	126.4	109.7	110.3	112.3	114.0	121.5	127.1	131.5	133.5	136.3	138.2	141.4	141.4
Structural Supports Insulation & Paint	172.4	145.0	147.5	155.0	158.5	165.1	173.4	173.5	180.8	188.1	187.4	191.9	192.4

SOURCE: Chemical Engineering, Economic Indicators

Table B-1 CHEMICAL ENGINEERING PLANT COST INDEXES (cont'd)

INDEX	1973 ANNUAL	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
CE Plant Index	144.1	140.8	140.4	141.5	141.8	142.4	144.5	144.6	145.0	146.4	146.7	147.5	148.2
Engineering & Supervision	122.84	112.0	112.0	122.3	122.4	112.5	129.8	130.1	130.1	130.1	130.7	130.8	131.3
Building	150.6	146.5	146.9	148.3	150.3	151.1	150.4	149.8	150.4	153.0	150.9	154.7	155.0
Construction Labor	157.9	158.9	155.8	154.8	155.0	155.4	155.6	156.3	156.3	161.8	161.7	161.6	162.0
Equipment, Machinery Supports	141.9	138.3	138.8	140.7	140.9	141.7	142.2	142.1	142.0	142.6	143.5	144.3	145.2
Fabricated Equipment	142.5	140.0	140.0	140.9	141.7	142.6	143.0	143.0	143.0	143.4	143.7	144.1	144.8
Process Machinery	137.6	134.3	134.5	135.1	137.1	137.6	137.9	137.9	138.5	139.1	139.6	140.3	142.0
Pipe, Valves & Fittings	151.3	146.1	146.1	149.2	150.1	151.1	151.7	151.8	151.8	151.8	153.9	156.6	157.8
Process Instruments & Controls	147.1	145.0	144.9	145.8	146.1	146.9	146.9	147.0	147.4	147.9	148.1	148.8	150.4
Pumps & Compressors	139.5	137.0	137.0	138.4	138.4	138.4	141.3	140.9	140.9	140.9	140.8	141.4	142.4
Electrical Equipment & Materials	104.2	100.6	100.6	102.1	103.9	104.5	105.2	105.1	105.1	105.1	105.3	106.0	107.2
Structural Supports Insulation & Paint	140.9	137.2	137.2	140.0	141.2	142.0	141.8	141.2	141.2	141.2	141.5	143.5	142.8

SOURCE: Chemical Engineering, Economic Indicators

Table B-1 CHEMICAL ENGINEERING PLANT COST INDEXES (cont'd)

INDEX	1972 ANNUAL	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
CE Plant Index	137.2	136.0	136.0	137.0	137.1	137.1	136.5	136.5	137.0	137.8	138.2	138.4	139.1
Engineering & Supervision	111.9	111.8	111.9	111.7	111.6	111.9	111.9	112.0	112.1	112.1	112.0	112.1	112.1
Building	142.0	139.8	140.0	140.7	141.4	141.6	140.3	141.4	141.9	143.0	144.1	144.5	145.0
Construction Labor	152.2	151.9	151.6	150.8	151.3	151.7	149.7	149.7	150.6	153.1	154.5	154.7	156.7
Equipment, Machinery Supports	135.4	133.8	133.9	135.8	135.3	135.5	135.4	135.2	135.6	135.9	135.9	136.0	136.5
Fabricated Equipment	136.3	135.1	136.1	137.8	136.2	135.9	135.7	135.6	136.3	135.7	136.8	136.6	137.5
Process Machinery	132.1	130.5	129.6	131.8	132.2	132.2	132.2	132.2	132.3	132.9	132.9	133.1	133.6
Pipe, Valves & Fittings	142.9	141.4	141.9	143.1	143.1	143.2	143.3	142.9	142.9	143.0	143.3	143.6	143.6
Process Instruments & Controls	143.8	141.9	142.7	143.6	143.9	144.1	144.0	144.0	144.3	144.2	144.1	144.2	144.7
Pumps & Compressors	135.9	132.4	134.4	135.7	135.7	135.7	136.3	136.6	136.7	136.7	137.7	137.0	137.0
Electrical Equipment & Materials	99.1	98.2	98.3	98.2	98.6	99.1	99.4	99.3	99.5	99.4	99.3	100.0	100.1
Structural Supports Insulation & Paint	133.6	131.2	131.9	132.1	132.7	134.9	134.1	133.8	134.2	134.4	134.5	134.5	134.6

SOURCE: Chemical Engineering, Economic Indicators

Table B-1 CHEMICAL ENGINEERING PLANT COST INDEXES (cont'd)

INDEX	1971 ANNUAL	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
CE Plant Index	132.3	128.2	129.1	129.9	130.2	131.6	131.4	132.3	134.4	135.0	135.1	134.9	135.3
Engineering & Supervision	111.4	111.1	111.2	111.2	111.3	111.4	111.3	111.4	111.4	111.5	111.6	111.6	111.7
Building	135.5	130.0	131.5	132.9	132.9	134.3	133.6	136.2	138.2	139.0	138.9	138.8	139.2
Construction Labor	146.2	142.5	143.3	142.8	142.5	144.2	144.0	146.1	147.4	149.9	150.4	150.1	150.6
Equipment, Machinery Supports	130.4	125.7	126.7	128.0	128.6	130.0	130.0	130.3	133.1	133.1	133.0	132.7	133.2
Fabricated Equipment	130.3	125.5	125.6	127.9	128.8	129.6	129.3	129.4	133.4	133.5	133.5	133.4	134.1
Process Machinery	127.1	125.4	125.7	126.3	126.5	127.1	127.6	128.4	129.4	129.5	129.4	129.4	130.4
Pipe, Valves & Fittings	137.3	131.0	132.0	132.7	133.9	137.7	137.7	138.0	141.2	141.1	140.9	140.2	140.7
Process Instruments & Controls	139.9	134.0	138.6	139.3	139.6	140.0	140.2	140.7	141.5	141.2	141.2	141.1	141.5
Pumps & Compressors	133.2	129.1	135.8	135.8	132.5	133.1	133.1	133.1	133.7	133.7	133.7	132.4	132.4
Electrical Equipment & Materials	98.7	101.1	100.2	99.2	98.8	98.5	98.1	97.9	98.6	98.3	98.3	97.7	97.7
Structural Supports Insulation & Paint	126.6	120.1	120.6	123.6	124.5	126.6	126.7	127.5	132.2	131.9	131.9	131.9	132.0

SOURCE: Chemical Engineering, Economic Indicators

Table B-1 CHEMICAL ENGINEERING PLANT COST INDEXES (cont'd)

INDEX	1970 ANNUAL	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
CE Plant Index	125.7	123.1	123.0	123.7	124.5	125.0	125.4	126.2	127.0	127.6	127.6	128.0	127.7
Engineering & Supervision	110.6	110.3	110.4	110.5	110.6	110.5	110.6	110.7	110.8	110.8	110.8	110.9	110.0
Building	127.2	125.0	124.6	124.7	125.5	126.2	126.1	127.4	128.6	130.1	130.1	129.7	129.5
Construction Labor	137.4	134.6	134.1	134.6	134.7	134.7	134.8	136.6	139.0	141.4	141.4	141.7	141.4
Equipment, Machinery Supports	123.8	120.8	120.9	122.2	123.0	123.7	124.4	124.9	125.1	125.1	125.1	125.6	125.3
Fabricated Equipment	122.7	118.5	118.8	121.1	122.2	122.5	124.0	124.1	124.2	123.8	123.8	124.0	124.8
Process Machinery	122.9	120.1	119.1	121.4	121.8	122.2	122.7	123.3	123.5	124.8	124.3	127.2	124.9
Pipe, Valves & Fittings	132.0	130.3	130.4	130.0	130.5	132.9	133.0	133.8	133.9	132.4	132.4	133.0	131.6
Process Instruments & Controls	132.1	130.6	130.8	130.9	131.2	131.5	132.0	132.0	132.6	133.6	133.6	133.7	133.7
Pumps & Compressors	125.6	123.1	123.1	123.7	124.8	124.1	124.1	125.6	125.6	129.1	129.1	129.2	129.1
Electrical Equipment & Materials	99.8	96.8	97.6	98.3	98.3	98.7	98.9	100.8	101.5	102.1	102.1	101.8	101.1
Structural Supports Insulation & Paint	117.9	114.7	114.9	116.7	117.7	118.1	118.5	118.9	118.9	119.4	119.4	118.9	119.0

SOURCE: Chemical Engineering, Economic Indicators

Table B-1 CHEMICAL ENGINEERING PLANT COST INDEXES (cont'd)

INDEX	1969 ANNUAL	1968 ANNUAL	1967 ANNUAL	1966 ANNUAL	1965 ANNUAL	1964 ANNUAL	1963 ANNUAL	1962 ANNUAL	1961 ANNUAL	1960 ANNUAL	1959 ANNUAL	1958 ANNUAL	1957 ANNUAL
CE Plant Index	119.0	113.6	109.7	107.2	104.2	103.3	102.4	102.0	101.5	102.0	101.8	99.7	98.5
Engineering & Supervision	110.9	108.6	107.9	106.9	105.6	104.2	103.4	102.6	101.7	101.3	102.5	99.3	98.2
Building	122.5	115.7	110.3	107.9	104.5	103.3	102.1	101.4	100.8	101.5	101.4	99.5	99.1
Construction Labor	128.3	120.9	115.8	112.5	109.5	108.5	107.2	105.6	105.1	103.7	101.4	100.0	98.6
Equipment, Machinery Supports	116.6	111.5	107.7	105.3	102.1	101.2	100.5	100.6	100.2	101.7	101.9	99.6	98.5
Fabricated Equipment	115.1	109.9	106.2	104.8	103.4	102.7	101.7	101.0	100.1	101.2	100.9	99.6	99.5
Process Machinery	116.8	112.1	108.7	106.1	103.6	102.5	102.0	101.9	101.1	101.8	101.8	100.1	98.1
Pipe, Valves & Fittings	123.1	117.4	113.0	109.6	103.0	101.6	100.7	100.6	101.1	104.1	103.3	98.8	97.9
Process Instruments & Controls	126.1	120.9	115.2	110.0	106.5	105.8	105.7	105.9	105.9	105.4	102.9	100.4	96.7
Pumps & Compressors	119.6	115.2	111.3	107.7	103.4	101.0	100.1	101.1	100.8	101.7	102.5	100.0	97.5
Electrical Equipment & Materials	92.8	91.4	90.1	86.4	84.1	85.5	87.6	89.4	92.3	95.7	101.0	100.6	98.4
Structural Supports Insulation & Paint	112.6	105.7	102.1	101.0	98.8	98.3	97.3	99.2	99.8	101.9	101.6	100.4	98.0

SOURCE: Chemical Engineering, Economic Indicators

Table B-2 WHOLESALE PRICE INDEXES FOR COTTON BROADWOVEN GOODS, BLS # 0312, 1967=100

MONTH	1971	1972	1973	1974	1975	1976	1977
JAN	108.0	116.9	127.7	170.6	167.3		
FEB	108.2	118.0	130.3	172.4	163.3		
MAR	108.5	119.6	132.0	173.0	161.3		
APR	109.0	120.5	135.8	174.8	163.9		
MAY	109.8	121.5	137.8	174.7	168.6	Discontinued	
JUN	111.0	122.9	141.8	184.4	170.6		
JUL	112.1	123.3	146.2	188.5	173.7		
AUG	112.2	123.1	147.7	185.4	175.7		
SEP	111.6	124.4	152.0	184.6	176.6		
OCT	111.6	125.2	154.4	178.3	189.2		
NOV	112.1	125.7	160.6	176.0	195.3		
DEC	113.1	126.4	165.5	171.1	199.6		
ANNUAL	110.6	122.3	144.3	177.8	175.4		

Table B-3 WHOLESALE PRICE INDEXES FOR MANMADE FIBER BROADWOVEN GOODS, BLS #0334, 1967=100

MONTH	1971	1972	1973	1974	1975	1976	1977
JAN	94.1	111.5	124.7	159.7	146.7		
FEB	94.0	112.5	125.8	161.5	144.7		
MAR	94.6	112.7	133.0	161.7	128.4		
APR	96.8	114.9	139.4	162.7	128.3		
MAY	99.2	116.6	145.3	168.3	131.6	Discontinued	
JUN	102.4	118.0	147.7	173.4	134.5		
JUL	103.6	118.6	147.1	169.2	139.9		
AUG	106.0	118.4	147.8	165.3	143.1		
SEP	106.1	118.2	152.8	160.7	143.1		
OCT	105.1	118.3	154.9	154.6	147.1		
NOV	106.7	120.3	156.6	153.4	149.8		
DEC	109.3	122.4	158.4	149.9	149.6		
ANNUAL	101.5	116.9	144.5	161.7	140.6		

Table B-4 WHOLESALE PRICE INDEXES FOR RUBBER AND PLASTIC PRODUCTS

BLS # 07, 1967=100

MONTH	1971	1972	1973	1974	1975	1976	1977
JAN	108.4	109.5	110.0	117.7	149.6	152.3	164.6
FEB	109.1	109.2	110.1	119.8	150.0	154.1	164.2
MAR	109.1	108.9	110.3	123.8	149.7	155.5	164.6
APR	109.0	108.7	110.6	129.4	149.4	156.7	165.7
MAY	108.7	108.8	111.5	133.7	148.9	157.1	166.3
JUN	108.7	108.9	112.6	135.6	148.6	157.1	167.5
JUL	109.7	109.2	112.9	139.5	150.1	158.3	168.9
AUG	109.8	109.5	113.1	143.4	150.0	161.1	169.3
SEP	109.7	109.5	112.8	145.6	150.8	163.9	169.5
OCT	109.5	109.5	114.0	147.5	151.5	164.6	170.2
NOV	109.5	109.8	114.8	148.5	151.8	164.8	170.2
DEC	109.4	109.8	116.5	149.4	151.9	164.7	170.0
ANNUAL	109.2	109.3	112.4	136.2	150.2	159.2	167.6

Table B-5 WHOLESALE PRICE INDEXES FOR CARBON STEEL PLATES, A36

BLS # 10130246, 1967=100

MONTH	1971	1972	1973	1974	1975	1976	1977
JAN	119.0	141.0	146.7	152.1	212.9	219.8	240.2
FEB	119.0	141.0	146.7	152.1	212.9	219.8	240.2
MAR	128.8	141.0	146.7	161.3	212.9	219.8	240.2
APR	128.8	141.0	146.7	161.3	212.9	219.8	240.2
MAY	128.8	141.0	146.7	173.3	212.9	219.8	240.2
JUN	128.8	141.0	146.7	173.4	212.9	219.8	256.5
JUL	128.8	141.0	146.7	199.7	208.9	219.8	256.5
AUG	141.0	141.0	146.7	199.7	207.8	240.2	256.5
SEP	141.0	141.0	146.7	201.7	207.8	240.2	256.5
OCT	141.0	141.0	146.7	201.7	218.8	240.2	256.5
NOV	141.0	141.0	146.7	201.7	218.8	240.2	256.5
DEC	141.0	141.0	146.7	201.7	218.8	240.2	256.5
ANNUAL	132.3	141.0	146.7	181.6	213.2	228.2	248.4

Table B-6 WHOLESALE PRICE INDEXES FOR STAINLESS STEEL PLATE

BLS # 10130247, 1967=100

MONTH	1971	1972	1973	1974	1975	1976
JAN	140.2	146.1	132.8	134.2	197.1	206.3
FEB	140.2	146.1	132.8	134.3	195.7	206.3
MAR	140.2	121.3	132.8	139.2	195.7	206.3
APR	140.2	121.3	132.8	145.5	195.7	206.3
MAY	140.2	121.3	132.8	157.7	195.7	206.3
JUN	148.1	121.3	132.8	166.0	195.7	206.3
JUL	148.1	121.3	132.8	169.2	195.7	206.3
AUG	148.1	127.6	132.8	187.8	195.7	201.5
SEP	148.1	127.6	132.8	190.4	195.7	201.5
OCT	148.1	127.6	132.8	193.0	206.3	206.3
NOV	148.1	127.6	132.8	193.0	206.3	206.3
DEC	146.1	127.6	132.8	193.0	206.3	206.3
ANNUAL	144.6	128.1	132.8	166.9	198.5	205.5

Table B-7 WHOLESALE PRICE INDEXES FOR CARBON STEEL SHEET,

BLS #10130262, 1967=100

MONTH	1971	1972	1973	1974	1975	1976	1977
JAN	119.5	124.1	134.5	137.5	189.1	197.0	222.6
FEB	119.5	134.5	134.5	137.5	189.1	197.0	222.6
MAR	119.5	134.5	134.5	142.0	189.1	197.0	222.6
APR	119.5	134.5	134.5	146.6	189.1	197.0	222.6
MAY	119.5	134.5	134.5	155.8	185.0	197.0	222.6
JUN	119.5	134.5	134.5	165.4	185.0	209.1	222.6
JUL	127.5	134.5	134.5	182.3	184.8	209.1	237.4
AUG	127.5	134.5	134.5	188.5	184.8	209.1	237.4
SEP	127.5	134.5	134.5	188.5	184.8	209.1	237.4
OCT	127.5	134.5	137.5	188.5	197.0	209.1	237.4
NOV	127.5	134.5	137.5	188.5	197.0	209.1	237.4
DEC	127.5	134.5	137.5	190.0	197.0	220.9	237.4
ANNUAL	123.5	133.6	135.3	167.6	189.3	205.0	230.0

Table B-8 WHOLESALE PRICE INDEXES FOR STAINLESS STEEL SHEET
BLS # 10130264, 1967=100

MONTH	1971	1972	1973	1974	1975	1976	1977
JAN	130.8	137.1	117.5	126.8	178.9	162.6	185.0
FEB	130.8	137.1	117.5	128.6	169.6	162.6	186.6
MAR	130.8	138.1	117.5	134.9	169.3	164.2	186.6
APR	130.8	138.1	117.5	140.1	169.3	164.2	186.6
MAY	130.8	138.1	123.4	153.6	169.3	164.2	200.1
JUN	138.1	120.4	124.5	159.6	162.6	164.2	203.4
JUL	138.1	120.4	124.5	163.9	162.9	164.2	205.6
AUG	138.1	117.5	124.5	173.1	162.9	174.4	205.6
SEP	138.1	117.5	124.5	174.9	162.9	176.3	202.7
OCT	138.1	117.5	124.5	174.9	162.4	176.3	202.7
NOV	138.1	117.5	124.6	175.8	156.9	176.3	200.3
DEC	137.1	117.5	124.6	178.9	156.7	176.3	200.3
ANNUAL	135.0	126.4	122.1	157.1	165.3	168.8	197.1

Table B-9 WHOLESALE PRICE INDEXES FOR PUMPS, COMPRESSORS, AND EQUIPMENT
BLS # 1141, 1967=100

MONTH	1971	1972	1973	1974	1975	1976	1977
JAN	119.3	122.4	125.0	132.1	180.5	192.2	205.5
FEB	120.0	123.2	125.1	133.4	184.3	194.9	205.3
MAR	120.5	123.5	125.2	135.5	184.4	195.8	206.4
APR	121.6	123.5	125.9	138.7	186.2	196.2	206.6
MAY	121.9	123.0	126.2	142.5	187.3	195.9	209.2
JUN	121.9	124.2	127.7	147.7	187.3	197.4	210.3
JUL	121.9	124.9	127.5	154.0	187.9	197.5	212.9
AUG	122.3	124.6	127.7	162.7	188.8	198.5	213.7
SEP	122.3	124.6	127.6	163.8	189.2	199.6	215.1
OCT	122.6	124.7	128.6	168.8	189.9	200.9	216.0
NOV	122.2	124.8	131.4	176.8	191.3	201.4	218.5
DEC	122.2	124.8	131.7	179.5	191.1	203.6	219.1
ANNUAL	121.6	124.0	127.5	153.0	187.4	197.8	211.6

Table B-10 WHOLESALE PRICE INDEXES FOR V-BELT SHEAVES

BLS # 11450133, 1967=100

MONTH	1971	1972	1973	1974	1975	1976	1977
JAN	117.6	117.6	126.3	130.4	175.4	175.6	180.7
FEB	117.6	117.6	126.3	133.3	175.4	175.6	192.3
MAR	117.6	117.6	126.3	133.3	175.4	175.6	192.3
APR	117.6	122.4	126.3	133.3	175.4	179.7	192.3
MAY	117.6	124.4	126.3	137.7	174.1	179.7	210.1
JUN	117.6	126.3	126.3	139.9	174.1	184.4	210.1
JUL	117.6	126.3	126.3	150.9	174.1	184.4	210.1
AUG	117.6	126.3	126.3	162.6	172.8	184.4	210.1
SEP	117.6	126.3	126.3	162.6	172.8	184.4	213.7
OCT	117.6	126.3	126.3	171.6	172.8	184.4	213.7
NOV	117.6	126.3	128.2	171.6	175.6	180.7	213.7
DEC	117.6	126.3	130.4	175.4	175.6	180.7	213.7
ANNUAL	117.6	123.6	126.8	150.2	174.5	180.8	204.4

Table B-11 WHOLESALE PRICE INDEXES FOR FANS AND BLOWERS, EXCEPT PORTABLE

BLS # 1147, 1967=100

MONTH	1971	1972	1973	1974	1975	1976	1977
JAN	120.8	125.6	132.4	138.2	197.9	206.5	224.7
FEB	121.0	127.3	132.6	138.5	198.2	207.1	226.4
MAR	123.1	128.6	133.1	145.5	198.6	210.1	226.8
APR	122.2	128.8	134.4	146.4	198.8	213.9	224.1
MAY	122.2	128.8	134.4	158.6	201.3	214.1	224.8
JUN	124.6	128.8	135.0	171.8	202.4	214.2	228.8
JUL	124.9	128.8	135.0	178.6	205.4	216.0	230.5
AUG	124.9	128.8	135.2	183.2	205.4	216.0	231.1
SEP	125.3	129.9	137.5	185.3	205.8	216.1	233.7
OCT	125.3	130.0	137.7	188.6	206.4	221.7	233.9
NOV	125.3	130.0	137.6	192.3	206.6	221.7	233.9
DEC	125.5	122.4	137.6	192.6	206.5	221.9	234.4
ANNUAL	123.8	129.0	135.2	168.3	202.8	214.9	229.4

Table B-12 WHOLESALE PRICE INDEXES FOR MOTORS, INTEGRAL HORSEPOWER, A.C., 10 HP BLS # 11730112, 1967=100

MONTH	1971	1972	1972	1974	1975	1976	1977
JAN	122.1	99.6	112.1	125.8	184.0	192.2	204.4
FEB	113.6	99.6	112.1	125.8	186.1	193.6	204.4
MAR	109.1	99.6	115.2	127.9	186.1	193.6	211.4
APR	104.0	101.1	118.2	130.9	186.1	193.6	207.9
MAY	104.0	105.6	119.7	134.9	186.1	193.6	207.9
JUN	104.0	105.6	120.9	155.1	N/A	193.6	211.4
JUL	102.2	105.6	120.9	160.0	N/A	195.7	218.5
AUG	101.6	105.6	120.9	161.7	186.1	197.8	218.5
SEP	101.6	105.6	119.7	167.6	186.1	202.1	218.5
OCT	101.6	105.6	119.7	172.4	186.1	204.4	218 5
NOV	101.6	111.5	121.8	175.9	186.1	204.4	218.5
DEC	101.6	111.5	124.2	179.8	186.1	204.4	218.5
ANNUAL	105.6	104.7	118.8	151.5	185.9	197.4	213.2

N/A = Not Available

Table B-13 WHOLESALE PRICE INDEXES FOR MOTORS, INTEGRAL HORSEPOWER, A.C., 250 HP BLS # 11730113, 1967=100

MONTH	1971	1972	1973	1974	1975	1976	1977
JAN	123.9	125.1	129.5	142.0	N/A	N/A	N/A
FEB	123.9	125.1	129.5	143.9	N/A	N/A	N/A
MAR	123.9	125.1	131.9	143.9	N/A	N/A	N/A
APR	125.6	127.8	136.3	141.3	N/A	N/A	N/A
MAY	129.0	127.8	136.3	N/A	N/A	N/A	N/A
JUN	129.0	127.8	136.3	N/A	N/A	N/A	N/A
JUL	130.7	127.8	139.3	N/A	N/A	N/A	N/A
AUG	130.7	129.5	139.3	N/A	N/A	N/A	N/A
SEP	130.7	129.5	139.3	N/A	N/A	N/A	N/A
OCT	130.7	129.5	139.3	N/A	N/A	N/A	N/A
NOV	130.7	129.5	139.3	N/A	N/A	N/A	N/A
DEC	130.7	129.5	139.3	N/A	N/A	N/A	N/A
ANNUAL	128.3	127.8	136.3	142.8	N/A	N/A	N/A

N/A = Not Available

Table B-14 WHOLESALE PRICE INDEXES FOR MOTORS, INTEGRAL HORSEPOWER, A.C., 50 HP
BLS # 11730119, 1967=100

MONTH	1971	1972	1973	1974	1975	1976	1977
JAN	115.1	99.6	111.5	123.5	178.0	186.6	200.6
FEB	98.9	99.6	111.5	123.5	180.6	190.1	200.6
MAR	98.9	99.6	113.4	126.1	184.9	191.9	200.6
APR	98.2	101.5	117.1	126.1	184.9	191.9	200.6
MAY	98.2	105.6	119.0	140.7	184.9	191.9	200.6
JUN	98.2	105.6	120.5	152.4	184.9	191.9	204.1
JUL	95.9	105.6	120.5	160.9	184.9	191.9	216.3
AUG	95.2	105.6	120.5	163.1	184.9	194.5	216.3
SEP	95.2	105.6	119.0	164.3	184.9	200.6	216.3
OCT	95.2	105.6	119.0	172.8	184.9	200.6	216.3
NOV	95.2	111.5	119.0	172.8	184.9	200.6	216.3
DEC	95.2	111.5	120.1	172.8	184.9	200.6	216.3
ANNUAL	98.3	104.7	117.6	149.9	184.0	194.4	208.7

Table B-15 WHOLESALE PRICE INDEXES FOR A.C. STARTERS, 75 HP, 440 VOLTS
BLS #11750781, 1967=100

MONTH	1971	1972	1973	1974	1975	1976	1977
JAN	106.8	112.4	112.4	115.4	143.7	152.0	163.3
FEB	105.5	112.4	112.4	116.1	143.7	152.0	163.2
MAR	105.5	112.4	112.4	116.1	143.7	152.0	163.2
APR	105.5	112.4	112.4	116.1	143.7	150.0	163.2
MAY	105.5	112.4	112.4	123.4	143.7	152.0	163.2
JUN	105.5	112.4	112.4	130.0	143.7	152.0	163.2
JUL	105.7	112.4	112.4	132.0	143.7	152.0	163.2
AUG	112.4	112.4	112.4	132.0	143.7	152.0	163.2
SEP	112.4	112.4	112.4	133.0	147.0	155.0	166.2
OCT	112.4	112.4	112.4	141.0	N/A	163.3	173.8
NOV	112.4	112.4	112.4	143.7	150.3	163.3	176.3
DEC	112.4	112.4	112.4	143.7	146.7	163.3	176.3
ANNUAL	108.5	112.4	112.4	128.5	144.9	154.9	166.5

Table B-16 WHOLESALE PRICE INDEXES FOR REFRACTORIES

BLS # 135, 1967=100

MONTH	1971	1972	1973	1974	1975	1976	1977
JAN	126.7	127.1	136.3	136.3	161.2	179.7	193.1
FEB	126.7	127.1	136.3	136.3	163.3	179.7	193.2
MAR	126.7	127.1	136.3	136.3	163.5	179.9	193.2
APR	126.7	127.1	136.3	136.3	163.6	180.3	193.3
MAY	126.7	127.1	136.3	136.3	163.7	180.2	194.3
JUN	126.9	127.1	136.3	136.3	163.7	180.4	196.5
JUL	126.9	127.1	136.3	137.8	163.8	180.7	197.3
AUG	126.9	129.6	136.3	137.8	164.0	181.2	198.5
SEP	126.9	132.1	136.3	153.4	164.2	188.9	207.1
OCT	127.1	132.1	136.3	157.0	164.3	191.1	208.5
NOV	127.1	132.1	136.3	157.8	177.0	193.0	209.3
DEC	127.1	132.1	136.3	160.5	179.7	192.9	209.3
ANNUAL	126.9	129.0	136.3	143.5	166.0	184.0	199.5

Table B-17 WHOLESALE PRICE INDEXES FOR FIRE CLAY BRICK, SUPER DUTY

BLS # 13520111, 1967=100

MONTH	1971	1972	1973	1974	1975	1976	1977
JAN	129.0	129.0	134.5	134.5	167.1	194.1	207.9
FEB	129.0	129.0	134.5	134.5	170.3	194.1	207.9
MAR	129.0	129.0	134.5	134.5	170.3	194.1	207.9
APR	129.0	N/A	134.5	134.5	170.3	194.1	207.9
MAY	129.0	N/A	N/A	134.5	170.3	194.1	207.9
JUN	129.0	N/A	134.5	134.5	170.3	194.1	207.9
JUL	129.0	129.0	N/A	135.3	170.3	194.1	209.7
AUG	129.0	131.0	N/A	N/A	170.3	195.1	210.8
SEP	129.0	132.3	134.5	156.0	170.3	199.8	218.4
OCT	129.0	N/A	134.5	164.2	170.3	201.9	220.8
NOV	129.0	132.3	134.5	164.2	189.2	206.9	222.3
DEC	129.0	132.3	N/A	167.1	194.1	206.9	222.3
ANNUAL	129.0	130.5	134.5	144.9	173.6	197.4	212.9

N/A = Not Available

Table B-18 WHOLESALE PRICE INDEXES FOR HIGH ALUMINA BRICK, 70 PCT. BLS # 13520131, 1967=100

MONTH	1971	1972	1973	1974	1975	1976	1977
JAN	119.8	122.7	146.9	146.9	183.4	211.5	224.7
FEB	119.8	122.7	146.9	146.9	189.0	211.5	224.7
MAR	119.8	122.7	146.9	146.9	189.0	212.9	224.7
APR	119.8	N/A	146.9	146.9	190.1	212.9	224.7
MAY	119.8	N/A	N/A	146.9	190.1	212.9	227.6
JUN	121.5	N/A	146.9	146.9	190.1	212.9	229.6
JUL	121.5	122.7	N/A	154.6	190.1	215.5	229.6
AUG	121.5	130.4	N/A	N/A	192.4	215.5	229.6
SEP	121.5	134.5	146.9	170.4	192.4	219.3	240.0
OCT	122.7	N/A	146.9	178.7	192.4	221.1	242.6
NOV	122.7	134.5	146.9	178.7	209.3	224.7	244.5
DEC	122.7	134.5	N/A	181.2	211.5	224.7	244.5
ANNUAL	121.1	128.1	146.9	158.6	193.3	216.3	232.2

N/A = Not Available

Table B-19 WHOLESALE PRICE INDEXES FOR CASTABLE REFRACTORIES BLS # 13520151, DEC 1974=100

MONTH	1975	1976	1977
JAN	100.8	109.9	116.9
FEB	100.8	109.9	116.9
MAR	100.8	110.0	116.9
APR	101.9	110.0	116.9
MAY	101.9	110.0	116.9
JUN	101.9	110.0	116.9
JUL	101.9	110.0	117.6
AUG	102.7	110.8	117.6
SEP	102.7	112.3	123.2
OCT	102.7	113.2	123.2
NOV	105.3	116.2	125.1
DEC	108.6	116.2	125.1
ANNUAL	102.7	111.6	119.4

Table 20 WHOLESALE PRICE INDEXES FOR INSULATION MATERIALS
BLS #1392, 1967=100

MONTH	1971	1972	1973	1974	1975	1976	1977
JAN	126.2	134.5	137.5	139.2	189.7	201.4	223.1
FEB	126.2	134.5	137.5	139.2	189.7	201.4	223.1
MAR	126.2	134.5	138.4	139.2	189.7	215.7	228.2
APR	126.2	134.5	138.4	139.9	189.7	210.6	228.2
MAY	134.5	142.7	138.4	146.9	189.7	210.5	228.2
JUN	134.5	138.8	138.4	149.8	194.1	210.5	236.4
JUL	134.5	136.8	138.4	152.0	203.0	210.2	238.1
AUG	134.5	136.8	138.4	156.0	203.0	210.2	238.7
SEP	134.5	137.5	135.0	169.6	201.4	219.1	251.7
OCT	134.5	137.5	135.0	169.6	201.4	220.6	244.9
NOV	134.5	137.5	135.0	187.2	201.4	220.6	245.3
DEC	134.5	137.5	137.9	189.2	201.4	220.6	244.5
ANNUAL	131.7	136.9	137.4	150.5	192.2	212.6	235.9

Table B-21 WHOLESALE PRICE INDEXES FOR NATURAL GAS
BLS # 05310101, 1967 = 100

MONTH	1971	1972	1973	1974	1975	1976	1977
JAN	109.5	116.3	125.1	140.9	180.5	236.1	331.1
FEB	107.9	116.6	125.4	145.0	190.5	236.1	384.2
MAR	109.7	117.6	125.8	147.8	190.0	248.5	392.8
APR	110.8	119.6	127.4	148.4	205.8	257.0	405.0
MAY	112.2	120.3	129.1	149.8	222.0	259.8	420.2
JUN	113.0	120.2	130.1	151.7	219.7	273.0	410.3
JUL	113.0	120.6	131.1	152.6	228.3	279.0	N/A
AUG	112.6	122.1	133.3	154.3	223.1	294.1	N/A
SEP	114.2	122.8	135.8	159.8	229.4	294.3	N/A
OCT	114.7	123.9	135.9	162.1	229.5	356.8	N/A
NOV	114.7	125.9	135.4	173.1	225.7	408.1	N/A
DEC	113.5	126.2	141.5	175.3	239.5	360.6	N/A
ANNUAL	112.8	121.0	131.3	155.1	215.3	292.0	N/A

N/A Not Available

Table B-22 WHOLESALE PRICE INDEXES FOR INDUSTRIAL POWER, 500 KWD
BLS # 0543, Dec 1967 = 100

MONTH	1971	1972	1973	1974	1975	1976	1977
JAN	112.7	121.2	126.9	142.3	198.3	216.4	234.7
FEB	113.5	122.7	129.0	147.0	202.7	217.5	241.7
MAR	115.1	122.5	130.1	154.3	208.0	220.8	248.2
APR	115.5	123.0	131.0	158.8	212.5	224.6	256.4
MAY	116.1	123.9	131.5	166.8	208.7	224.1	257.2
JUN	116.3	124.0	131.2	174.1	206.0	225.1	256.0
JUL	118.0	124.3	131.8	178.1	207.5	228.9	262.5
AUG	119.5	124.4	132.0	182.2	210.5	231.9	269.2
SEP	119.4	124.9	134.0	185.2	213.7	233.8	265.9
OCT	119.3	125.4	135.6	191.0	215.8	231.6	267.3
NOV	119.5	125.4	137.3	193.2	217.2	233.5	262.2
DEC	122.6	125.6	140.3	195.1	215.2	232.3	262.3
ANNUAL	117.3	123.9	132.6	172.3	209.7	226.7	257.0

Table B-23 INDEXES OF AVERAGE HOURLY EARNINGS: MANUFACTURING
1967 = 100

MONTH	1971	1972	1973	1974	1975	1976	1977
JAN		132.1	139.5	148.7	164.8	178.8	192.3
FEB		132.7	139.7	149.6	166.1	180.0	193.4
MAR		133.2	140.4	150.6	167.7	180.9	194.3
APR		133.6	141.1	151.7	168.6	181.9	195.6
MAY		134.5	141.8	153.5	169.7	182.5	196.9
JUN		135.0	142.7	155.5	171.0	183.6	198.5
JUL		135.5	143.7	156.6	172.2	185.3	200.3
AUG		136.1	144.5	158.0	173.3	186.6	201.2
SEP		136.8	145.4	159.6	174.5	188.0	202.7
OCT	129.3	137.5	146.5	161.3	176.0	188.4	204.2
NOV	129.0	138.0	147.0	162.5	177.0	189.8	205.4
DEC	131.3	138.8	147.9	163.7	177.4	191.0	206.3
ANNUAL	127.5	135.4	143.6	156.0	171.5	184.7	199.3

SOURCE: U.S. Dept. of Commerce, Survey of Current Business

APPENDIX C

GUIDE TO REFERENCES TO THE INDUSTRIES

LIST OF REFERENCES CROSS-INDEXED TO INDUSTRY SOURCE

INDUSTRY (or source of pollution)	List of References
Basic Oxygen Furnaces	5, 10, 11, 15, 24, 26, 34, 35, 36, 117
Brick Manufacturing	5, 24, 26, 35, 36, 82, 96, 97
Castable Refractories	5, 10, 26, 96, 97
Clay Refractories	5, 6, 24, 26, 36, 52, 96, 97
Coal Fired Boilers	5, 6, 15, 24, 26, 34, 35, 36, 52, 61, 71, 76, 77, 83, 115, 123
Conical Incinerators	5, 15, 26, 113, 116, 117
Cotton Ginning	10, 26
Detergent Manufacturing	5, 10, 24
Electric Arc Furnaces	5, 10, 11, 15, 16, 17, 24, 26, 28, 34, 35, 36, 67, 103, 104, 117
Feed Mills	5, 10, 24, 26, 35, 78, 80, 117, 118
Ferroalloy Plants	5, 10, 11, 15, 24, 26, 67, 82, 89, 99, 117, 167
Glass Manufacturing	24, 36, 117, 167
Grey Iron Foundries	5, 6, 10, 15, 16, 17, 24, 26, 28, 32, 35, 37, 55, 78, 93, 101, 110, 117
Iron & Steel (Sintering)	5, 6, 10, 11, 15, 24, 26, 34, 35, 36, 37, 56, 82, 102, 103, 104, 105, 110, 117
Kraft Recovery Furnaces	1, 2, 3, 5, 10, 26, 27, 30, 31, 34, 35, 63, 64, 72, 82, 90, 112, 117, 167
Lime Kilns	4, 6, 15, 19, 26, 35, 78
Municipal Incinerators	6, 15, 25, 26, 34, 58, 92, 94, 106, 107, 114, 115, 116, 117
Petroleum Catalytic Cracking	5, 6, 15, 26, 34, 35, 37, 42, 82, 109. 117
Phosphate Fertilizer	5, 6, 10, 24, 26, 34, 35, 37, 78, 117
Phosphate Rock Crushing	5, 24, 26, 34, 36, 117
Polyvinyl Chloride Production	5, 10, 24, 36, 37, 43
Portland Cement	5, 6, 12, 15, 24, 26, 34, 35, 36, 74, 98, 11
Pulp and Paper (Fluidized Bed Reactor)	1, 2, 3, 5, 10, 15, 27, 30, 31, 34, 63, 64, 90, 101, 112, 117
Secondary Aluminum Smelters	5, 13, 15, 19, 26, 34, 35, 36, 69, 95, 117
Secondary Copper Smelters	5, 15, 19, 26, 34, 35, 36, 69, 95, 100 117
Sewage Sludge Incinerators	5, 15, 26, 59, 114, 116, 117
Surface Coatings - Spray Booths	24, 35, 37, 40, 42, 45, 57, 115
Multi-Industry General Articles	7, 8, 9, 14, 20-23, 24, 30, 33, 34, 37, 38, 39, 40, 41, 44, 46-51, 53, 54, 60, 61, 62, 65, 66, 68, 70, 71, 73, 75, 78, 79, 81, 82, 84, 85, 86, 87, 88, 91, 111, 115, 119-122, 124-127, 128, 129, 130, 131, 132, 133, 134, 136, 137, 143, 144, 145, 148

LIST OF REFERENCES

Source No.	Title	APTIC No.	NTIS No.
1	Anon., "Control of Atmospheric Emissions in the Wood Pulping Industry", Vol. 1, Mar. 15, 1970. Contract No. CPA 22-69-18, NAPCA.	21385	
2	Ibid Item #1, Vol. 3.	21724	
3	Ibid Item #1, Vol. 2.	21728	
4	Minnick, L. J., "Control of Particulate Emissions From Lime Plants", June 14, 1970. 63rd Annual Meeting APCA Paper 70-73.	27434	
5	Billings, C. E. and Wilder, J. E., "Engineering Analysis of the Field Performance of Fabric Filter Systems", June 14, 1970. 63rd Annual Meeting APCA Paper 70-129 (performed under NAPCA Contract CPA 22-69-38).	28580	
6	Anon., "Efficiency Versus Particle Size and Approximate Cost Information of Mechanical Collectors", IGCI Pub. M1, Jan. 1968.	28821	
7	Heneghan, W. F., "Activated Carbon - A Final Filter", Pollution Engineering, Jan/Feb, 1970, pp. 18-20.	29088	
8	Ashman, R.. "A Practical Guide to Industrial Dust Control", JIHVE, Mar. 1971, Vol. 38, pp. 273-282.	29089	
9	Anderson, L. W., "Odor Control in Rendering by Wet Scrubbing - A Case History"; 1970, Carolina By-Products Company, Greensboro, N.C.	29261	
10	Anon., "Pollution Control Update, 1970", McGraw-Hill, Modern Manufacturing, July 1970, 6 pp.	30462	
11	Vaiga, J., et al., "A Systems Analysis of the Iron & Steel Industry", Battelle, May, 1969.	30698	184577
12	Walling, I. C., "Cement Plant Dust Collectors", Pit & Quarry, July, 1971, 64(1):143-148.	31538	
13	Cook, C. C., et al., "Operating Experience With the Alcoa 398 Process for Fluoride Recovery", Alcoa, Journal of the Air Pollution Control Assoc., 21(8):479-483, Aug. 1971.	31567	

Source No.	Title	APTIC No.	NTIS No.
14	Wright T. J., et al., "A Model for Estimating Air Pollution Control Costs", TRW, 64th Annual Meeting APCA, June 27, 1971, Paper 71-144. Work performed under Contract PH 22-68-60 (EPA).	31747	
15	Anon., "An Electrostatic Precipitator Systems Study", SRI, Oct. 1970, NAPCA Contract CPA 22-69-73.	32021	198150
16	Anon., "Systems Analysis of Emissions and Emissions Control in the Iron Foundry Industry", Vol. II, Feb. 1971, EPA Contract CPA 22-69-106, A. T. Kearney & Co., Inc.	32247	198349
17	Ibid Item 16, Vol. I.	32251	198348
18	Ibid Item 16, Vol. III.	32252	198350
19	Anon., "Study of Technical and Cost Information for Gas Cleaning Equipment in the Lime and Secondary Non-Ferrous Metallurgical Industries", IGCI, NAPCA Contract CPA 70-150, Dec., 1970.	32248	198137
20	Anon., "Fabric Filter Systems Study", Vol. II, GCA Corp., Dec. 1970, NAPCA Contract CPA 22-69-38.	34691	200649
21	Ibid Item 20, Vol. I.	34698	200648
22	Ibid Item 20, Vol. IV.	34799	200651
23	Ibid Item 20, Vol. III.	34799	200650
24	Anon., "Air Pollution Control: A Practical Guide to Information Sources for Business, Industry, and Municipalities", Purdue University Libraries Industrial and Technical Information Service, Apr., 1974. Bibliography listing of sources.	34894	
25	Stear, J. R., "Municipal Incineration: A Review of the Literature", EPA, June, 1971, Office of Air Programs, RTP.	34955	200514
26	Anon., "Particulate Pollutant Systems Study", Vol. III, Handbook of Emission Properties, EPA Contract CPA 22-69-104, May, 1971, MRI.	35574	203522
27	Weiner, J. and Roth, L., "Air Pollution in the Pulp & Paper Industry", The Institute of Paper Chemistry, Bibliographic Series No. 237, Supplement I, 1970.	35581	

Source No.	Title	APTIC No.	NTIS No.
28	Greenberg, J. H., "Systems Analysis of Emissions: The Iron Foundry Industry", Chem Tech 1(12): 728-736, Dec. 1971.	35925	
29	Victor, I., "Control of Gases and Vapor Emissions From Industrial and Dry Cleaning Processes Comparing Efficiency and Operating Cost of Incineration, Absorption, Condensation and Absorption Methods", Dec., 1971, Conference paper preprint, U. S. Dept. of Commerce and WPCF.	37254	
30	Mueller, J. H., "Fume and Odor Control Systems Compared and Analyzed", Wood & Wood Products, 76(3): 48-50, Mar., 1971.	38195	
31	Anon., "Harmonizing Pulp and Paper Industry with Environment", Proc. of XV EUCEPA Conference, Rome, May 7, 1973.	59245	
32	Anon., "Economic Impact of Air Pollution Controls on Gray Iron Foundry Industry", NAPCA Pub. AP 74, Nov., 1970.		196500
33	Oglesby, Sabert, et al., "A Manual of Electrostatic Precipitator Technology, Part I - Fundamentals", SRI, PHS CPA 22-69-73, Aug. 25, 1973.		196380
34	Ibid Item 33, Part II, Application Areas.		196381
35	Anderson, H. S., et al., "User's Manual, Automated Procedures for Estimating Control Costs and Emission Reductions, Etc.", RTI, PHS CPA 70-60, 1970.		198779
36	Anon., "Engineering and Cost Effectiveness Study of Fluoride Emissions Control", Jan. 1972, Vol. I, EPA Contract EHSD 71-14.		207506
37	Rolke, R. W., et al., "Afterburner Systems Study", EPA EHSD 71-3, Aug. 1972.		212560
38	Calvert, J., et al., "Wet Scrubber System Study", Vol. I, Scrubber Handbook, APT, Inc.,EPA R2 72 118A, CPA 70-95, July, 1972.		213016
39	Ibid Item 38, Vol. II, Final Report and Bibliography.		213017
40	Juhola, A. J., "Package Sorption Device System Study", MSA Res. Corp., EPA R2 73 202, EHSD 71-2, Apr. 1973.		221138

Source No.	Title	APTIC No.	NTIS No.
41	Anon., "Proceedings of a Symposium on Control of Fine-Particulate Emissions, Etc.", 1974, U.S.-U.S.S.R. Working Group Stationary Source Air Pol. Control Technology.		235829
42	Anon., "Systems and Costs to Control Hydrocarbon Emissions from Stationary Sources.		236921
43	Carpenter, B. H., "Vinyl Chloride; An Assessment of Emissions Control Techniques and Costs", RTP, EPA/650/2. 74097 EPA 68-02-1325, Sept., 1974.		237343
44	Anon., "Proceedings, Symposium on the Use of Fabric Filters for the Control of Sub-Micron Particulates", EPA 650-2-74-043, EPA 68-02-1316, Meeting, 1974.		237629
45	Dowd, E. J., "Air Pollution Control Engineering and Cost Study of the Paint and Varnish Industry", ARI, EPA 450-3-74-031, EPA 68-02-0259, June, 1974.		238058
46	Anon., "Air Pollution: Control Techniques for Nitrogen Oxide", NATO Comm. on the Challenge of Modern Society, NATO CCMS 20, Oct., 1973.		240578
47	Ibid Item 46, Hydrocarbon and Organic Solvent,CCMS 19.		240577
48	Ibid Item 46, Carbon Monoxide, CCMS 18.		240576
49	Ibid Item 46, Particulates, CCMS 13.		240573
50	Ibid Item 46, Sulfur Oxide, CCMS 12.		240572
51	"Control Techniques For Particulate Air Pollutants", USNGW, 1969, AP-51.		190253
52	"Sulfur Codes Pose Dilemma for Coal", Envir. Sci. Tech., 4(12):1104-1106, Dec., 1970.	37826	
53	Diamant, R. M. E., "The Prevention of Pollution, Part XII", Heating and Ventilating Eng., 4-S(535): 398-406, Feb., 1972.	38620	
54	"Low Cost Electrostatic Precipitation", Filtration Separation, 9(1): 52-59 Jan/Feb, 1972.	38088	
55	Anon., "Ford's Michigan Casting Center, Environmental Control", Foundry, 100(3): F8-F11, Mar., 1972.	37498	
56	Anon., "When It Comes to Pollution Control, Steel Isn't Dawdling- It's Acting", 33 Mag. 10(1): 23-29, Jan., 1972.	36286	

Source No.	Title	APTIC No.	NTIS No.
57	Hayes, C. T., "Cut Industrial Pollution by Eliminating Gaseous Waste", Automation, Cleveland 18(3):64-65, Mar., 1971.	36516	
58	Fife, J. A., "Design of the Northwest Incinerator for the City of Chicago", Proc. of Nat'l. Incinerator Conf., Cincinnati, Ohio, 1970, pp. 149-160.	28261	
59	Sebastian, F. P. and Isheim, M. C., "Advances in Incineration and Resource Reclamation", Proc. of Nat'l. Incinerator Conf., Cincinnati, Ohio, 1970, pp. 71-78.	28262	
60	Mueller, J. H., "Cost Comparison for Burning Fumes and Odors", Pollution Eng. 3(6):18-30, Nov/Dec, 1971.	34716	
61	Jaeger, W. and Keilpart, T., "Pollution Control Can Pay Its Way - Even When Retrofit", Elec. Light Power, 48(6):73-75, June, 1970.	31915	
62	Ottaviano, V. B. and Lazan, S., "Air Pollution Abatement Market for the Sheet Metal Industry", Heating Air Conditioning Contractors, Vol. 62:26-31, Aug., 1971.	31805	
63	Burgess, T. L., et al., "Incineration of Malodorous Gases in Kraft Pulp Mills", Pulp Paper Mag. Can., 75(5):92-96, May, 1974.	63161	
64	Roberson, J. E., et al., "The NAPCA Study of the Control of Atmospheric Emissions in the Wood Pulping Industry", TAPPI, 54(2): 239-244, Feb., 1971.	28095	
65	Jones, A. H., "The Basics of Dust Collection", Plant Eng., 25(4):71-73, Feb. 18, 1971	27279	
66	Ellison, W., "Wet Scrubbers Popular for Air Cleaning", Power, 115(2):62-63, Feb., 1971.	27282	
67	Person, R. A., "Control of Emissions from Ferroalloy Furnace Processing", J. Metals, 23(4):17-29, Apr., 1971.	29325	
68	Mueller, J. H., "What It Costs to Control Process Odors", Food Eng., 43(4):62-65, Apr., 1971.	29299	
69	Swan, D., "Study of Costs for Complying with Standards for Control of Sulfur Oxide Emissions from Smelters", Mining Congr. J., 57(4):76-85, Apr., 1971.	29376	

Source No.	Title	APTIC No.	NTIS No.
70	Calvert, Seymour, "Source Control by Liquid Scrubbing", In: Air Pollution, Arthur C. Stern (Ed.), Vol. 3, 2nd Ed., N.Y., Academic Press, 1968.	30868	
71	Olds, F. C., "SO_2 Control: Focusing on New Targets", Power Eng., 75(8):24-29, Aug., 1971.	31673	
72	Lardieri, N. T., "Present Treatment Practices in Kraft Mills of Air-borne Effluents", Paper Trade J., 142(15):28-33, 14 April, 1958.	35660	
73	Taylor, D. H., "Recommendations for Dust Collection Systems", Metal Progr. 98(6):63, Dec., 1970.	35087	
74	Van DeWouwer, R., "Clinker Cooler Dust Collector Recovers 60 TPD at Inland's Winnepeg Plant", Pit Quarry, 64(7):104-105, Jan., 1972.	35990	
75	Alonso, J. R.F., "Estimating the Costs of Gas Cleaning Plants", Chem. Eng., 78(28):86-96.	35532	
76	Benson, J. R. and Corn. M., "Costs of Air Cleaning with Electrostatic Precipitators at TVA Steam Plants", J. Air Pollution Control Assoc., 24(4):340-348, Apr., 1974, 7 Refs.	61840	
77	Selzler, David R. and Watson, W. D., "Hot Versus Enlarged Electrostatic Precipitation of Fly Ash: A Cost-Effectiveness Study", J. Air Poll. Control Assoc., 24(2):115-121, Feb., 1974, 25 Refs.	58903	
78	Hardison, L.C., "Air Pollution Control Technology and Costs in Seven Selected Industries (Final Report)", Industrial Gas Cleaning Institute, Stamford, Conn. Office of Air and Water Programs, Contract 68-02-0289, Rept. EPA-450/3-73-010, IGCI Rept. 47-173, 724 p., Dec. 1973, 82 Refs.	62087	
79	Nichols, Richard A., "Hydrocarbon-Vapor Recovery" Chem. Eng., 80(6):85-92, 5 Mar., 1973. Presented at the Petroleum Mech. Engrg.Conf., New Orleans, La., Sept. 17-21, 1972.	60808	
80	Shannon, Larry J.; Gerstle, Richard W.; Gorman, P. G.; Epp, P.G.; Devitt, T. W.; Amick, R., "Emissions Control in the Grain and Feed Industry. Vol. I- Engineering and Cost Study", Midwest Res. Inst., Kansas City, Mo., Office of Air Quality Planning and Standards, Contract 68-02-0213, Rept. EPA 450/3-73-003a, 583 pp., Dec., 1973, 128 Refs.	59566	

Source No.	Title	APTIC No.	NTIS No.
81	Larson, Dennis M., "Control of Organic Solvent Emissions by Activated Carbon", Metal Finishing, 71(12):62-65, 70, Dec., 1973, 4 Refs.	56967	
82	Hardison, L.C. and Greathouse, Carroll A., "Air Pollution Control Technology and Costs in Nine Selected Areas (Final Report)", Industrial Gas Cleaning Inst., Stamford, Conn., EPA Contract 68-02-0301,APTD-1555, 616 pp., Sept.30, 1972, 74 Refs.	57616	
83	Schultz, E. A.; Miller, W.E.; Barnard, R. E.; and Horlacher, W. R., "The Cat-Ox Project at Illinois Power", Proc. Am. Power Conf., Vol. 34: 484-490, April, 1972.	60847	
84	Stout, Bruce G., "Selection of Air Pollution Control Equipment", Army Logistics Management Center, Texarkana, Tex., Product/Production Engineering Program. Training Center Rept. USAMC-ITC-2-71-12, 82 pp., July, 1971, 13 Refs.	62011	
85	Bagwell, F. A., Cox, L. F. and Pirsh, E. A., "Flue-Gas Filtering Proves Practical on Oil-Fired Unit", Elec. World, 171(10):26-27, Mar. 10, 1969.	58729	
86	Cosby, W. T. and Punch, G., "Cost and Performance of Filtration and Separation Equipment, Dust Filters and Collectors", Filtration Separation (Purley), 5(3):252-255, May/June, 1968, 1 Ref.	57907	
87	Squires, B. J., "New Developments in the Use of Fabric Filter Dust Collectors", Filtration Separation (Purley), 6(2):161-170, Mar/Apr, 1969, 5 Refs. Presented at the Filtration Society, London, 10 Sept., 1968.	57370	
88	Danielson, J. A., "Air Pollution Engineering Manual", Air Pollution Control District County of Los Angeles, U. S. Environmental Protection Agency, Pub. No. AP-40, May, 1973.		
89	Dealy, J. O. and Killin, A. M., "Engineering and Cost Study of the Ferroalloy Industry", U. S. EPA, EPA 450/2-74-008, May, 1974.		
90	Hendrickson, E. R., et al., "Control of Atmospheric Emission in the Wood Pulping Industry", Environmental Engineers, Inc. and J. E. Sirrine Co., Contract No. CPA 22-69-18, March, 1970, Report PB 190-351.		

Source No.	Title	APTIC No.	NTIS No.
91	Cadman, T. W., "Elements of Pollution Control Economics", ICARUS Corp., Dec., 1973.		
92	"Interim Guide of Good Practice for Incineration at Federal Facilities", U. S. Dept. of Health, Education, and Welfare, Nov., 1969.		
93	Cowen, P. S., "Cupola Emission Control", Gray and Ductile Iron Founder's Society, Cleveland, Ohio, 1967.		
94	Fernandes, J. H., "Incineration Air Pollution Control", Proceedings of1968 National Incinerator Conference, New York, N. Y., American Society of Mechanical Engineers, pp. 101-115.		
95	Anon., "Economic Impact of Proposed Water Pollution Controls on the Nonferrous Metals Manufacturing Industry"- Phase II, Environmental Protection Agency, EPA-230/1-75-041, March, 1975.		
96	Anon., "Development Document for Effluent Limitations Guidelines and Standards of Performance", Versar, Inc., April, 1975, The Clay, Gypsum, Refractory, and Ceramic Products Industries, Office of Water and Hazardous Materials, EPA, Contract No. 68-01-2633.		
97	Ibid Item 96, Volume III, December 1974.		
98	Kreichelt, T. E., et al., "Atmospheric Emissions from the Manufacture of Portland Cement", U. S. Dept. of Health, Education, and Welfare, 1967.		PB190236
99	Anon., "Development Document for Interim Final Effluent Limitations Guidelines and Proposed New Source Performance Standards for the Calcium Carbide Segment of the Ferroalloy Manufacturing Point Source Category", U. S. Environmental Protection Agency, February 1975, EPA 440/1-75/038, Group I, Phase II.		
100	Anon., "Development Document for Proposed Effluent Limitations Guidelines and New Source Performance Standards for the Secondary Copper Subcategory of the Copper Segment of the Nonferrous Metals Manufacturing Point Source Category, U. S. Environmental Protection Agency, November 1974, EPA 440/1-75/032-c, Group I, Phase II.		

Source No.	Title	APTIC No.	NTIS No.
101	Coughlin, R.W., et al., "Air Pollution and Its Control", American Institute of Chemical Engineers, Symposium Series 1972, Volume 68, No. 126.		
102	Anon., "Development Document for Proposed Effluent Limitations Guidelines and New Source Performance Standards for the Steel Making Segment of the Iron & Steel Manufacturing Point Source Category, U. S. Environmental Protection Agency, January, 1974, EPA 440/1-73/024.		
103	Anon., "Background Information for Standards of Performance: Electric Arc Furnaces in the Steel Industry", Volume 1 - Proposed Standards, October, 1974.		PB 237840
104	Ibid Item 103, Volume 2 - Test Data Summary, Report No. EPA-450/2-74-017b.		PB 237841
105	Anon., "Economic Analysis of the Proposed Effluent Guidelines for the Integrated Iron and Steel Industry", February, 1974, Environmental Protection Agency, Report No. EPA-230/1-73-027, A. J. Kearny, Contract No. 68-01-1545.		
106	Anon., Municipal Refuse Disposal, Institute for Solid Wastes of American Public Works Association, 1970, Public Administration Service, Chicago, Illinois.		
107	Anon., 1968 National Incinerator Conference, New York, N. Y., Sponsored by ASME Incinerator Division.		
108	Breaux, James C., Control of Particulate Matter in Asphalt Plants. Preprint, Louisiana Tech. Univ., Continuing Engineering Education Div., pp. 80-91, 1970 (Presented at the Institute on Aspects of Air Pollution Control, Ruston, LA, Oct. 8-9, 1970)	57401	
109	American Petroleum Inst., Wash. D. C., Committee on Refinery Environmental Control, Hydrocarbon Emissions From Refineries. # Pub-928, 64 p., July, 1973.	59178	
110	Remmers, K., Dust Extraction From Cupolas by Means of Venturi Tube Scrubbers, Giesserei (Duesseldorf), 52(7): 191-193, April 1, 1965, Translated from German, 11 p.	61061	
111	Cheremisinoff, Paul N., "Wet Scrubbers - A Special Report", Pollution Engineering, May, 1974, pp. 33-43.		

Source No.	Title	APTIC No.	NTIS No.
112	Bunyard, F. L., "Pollution Control for the Kraft Pulping Industry: Cost and Impact", Annual Meeting of the Air Pollution Control Association, June 14-19, 1970, APCA #70-74.		
113	Vickerson, George L., "Fly Ash Control Equipment for Industrial Incinerators", Proc. 1966 ASME Incinerator Conf.		
114	Guccione, Eugene, "Incineration Slashes Costs of Sewage Disposal", Chemical Engineering, Apr. 11, 1966, pp.144-146.		
115	"New Developments in Air Pollution Control", Proc. MECAR Symposium, New York, N.Y., Oct. 23, 1967.		
116	Corey, Richard, Principles and Practices of Incineration, Wiley-Interscience, New York, N.Y., 1969.		
117	Stern, Arthur C., Air Pollution, 2nd Ed., Vol. II & III, Academic Press, New York, 1968.		
118	Smith, Kenneth D., "Particulate Emissions from Alfalfa Dehydrating Plants -- Control Costs and Effectiveness", EPA-650/2-74-007, Jan., 1974.		
119	"Capital and Operating Costs of Pollution Control Equipment Modules", Vol. I & II, EPA-R5-73-023a & b, July, 1973.		224-53 224-53
120	Liptak, B. G., Environmental Engineers Handbook, Radnor, Chilton Book, 1974, 1340 p.		
121	Fraser, M. D. and Foley, G. J., Cost Models for Fabric Filter Systems. In: The 67th Annual Meeting of the Air Pollution Control Association, Denver, June, 1974, APCA # 74-96.		
122	Reigel, S. A., Bundy, R. P. and Doyle, C. D. Baghouses - What to Know Before You Buy. Pollution Engineering. 5:32-34, May, 1973.		
123	Walker, A. B. Experience with Hot Electrostatic Precipitators for Fly Ash Collection in Electric Utilities. In: American Power Conference, Chicago, Research-Cottrell, Inc., April 29-May 1, 1974.		
124	Alfonso, J. R. F. Estimating the Costs of Gas Cleaning Plants. Chemical Engineering, December 13, 1971, pp. 86-96.		
125	Schneider, G. G., Horzella, T. I., Cooper, J. and P. J. Striegl. Selecting and Specifying Electrostatic Precipitators. Chemical Engineering. 82 11:94-108, May, 1975.		

Source No.	Title	APTIC No.	NTIS No.
126	Anon. Survey of Electrostatic Precipitator Operating and Maintenance Costs. Water and Sewage Works, Reference Number - 1971, Aug. 31, 1971, pp. R236-R237.		
127	Rymarz, J. M. and Klipstein, D. H. Removing Particulates From Gases. Chemical Engineering. 82 (21): 113-120, October, 1975.		
128	"Estimating Costs and Manpower Requirements for Conventional Wastewater Treatment Facilities", EPA 17090 DAN 10/71.		PB 211132
129	Jorgensen, Robert, Editor, "Fan Engineering"; 6th Ed., Buffalo Forge Company, New York, 1961.		
130	Arnold, T. H. and Chilton, C. H., New Index Shows Plant Cost Trends, Chemical Engineering, Feb. 18, 1963, pp. 143-149.		
131	Economic Indicators, Chemical Engineering, Every Issue.		
132	Gorman, P. G., "Control Technology For Asphalt Roofing Industry", Midwest Research Institute, Kansas City, Mo., EPA Contract 68-02-1324, Rept. EPA 600/2-76-120, April 1976.		
133	Parsons, T. B., Shirley, T. E., Piana, M. B., "Hydrocarbon Control Cost Effectiveness Analysis for Nashville, Tenn.," Radian Corporation, Austin, TX., EPA Contract 68-02-2608, Rept. EPA 904/9-78-003, February, 1978.		
134	Burklin, C. E., Colley, S. D., Owen, M. L., "Background Information on Hydrocarbon Emissions From Marine Terminal Operations, Volume I, Discussion", Radian Corp., Austin, TX., EPA Contract 68-02-1319, Rept. EPA 450/3-76-038a, November, 1976.		
135	IBID Item 134, Volume II, Appendices, Rept. EPA 450/3-76-038b.		
136	Pitruzzello, V. J., "The Control of Hydrocarbon Emissions From Gasoline Marketing Operations," EPA, Proceedings of Air Pollution Control Association Annual Meeting, June, 1977.		

Source No.	Title	APTIC No.	NTIS No.
137	Burklin, C. E., Cavanaugh, E. C., Dickerman, J. C., Fernandes, S. R., "A Study of Vapor Control Methods For Gasoline Marketing Operations: Volume I - Industry Survey and Control Techniques," Radian Corp. Austin, TX, EPA Contract 68-02-1319, Rept. EPA 450/3-75-046a, April, 1975.		
138	Klett, M. G., Galeski, J. B., "Flare Systems Study", Lockheed Missiles and Space Co., Huntsville, AL, EPA Contract 68-02-1331, Rept. EPA 600/2-76-079, March, 1976.		
139	McIlvaine, R. W., Ardell, M., "Research and Development and Cost Projections for Air Pollution Control Equipment," The McIlvaine Co., Northbrook, IL, EPA P.O. DA-7-6086A, Rept. EPA-600/7-78-092, June, 1978.		
140	Bellegia, F. L., Mathews, J. D., Paddock, R. E., Wisler, M. M., "Update and Improvement of the Control Cost Segment of the Implementation Planning Program", EPA Contact 68-02-0607, February, 1975.		
141	Anon., "Report of Fuel Requirements, Capital Cost and Operating Expense for Catalytic and Thermal Afterburners", CE Air Preheater Industrial Gas Cleaning Institute, Stamford, Conn., EPA Contract 68-02-1473, Rept. EPA 450/3-76-031, September, 1976.		
142	Bryan, R. J., Yamada, M. M., Norton, R. L., Kokin, A., "Evaluation of Top Loading Vapor Balance Systems For Small Bulk Plants", EPA Contract 68-01-4140, Rept. EPA 340/1-77-014, April, 1977.		
143	Gammell, D. M., "Emission Control Technology For Marine Terminals Handling Crudes and Gasoline", Robert Brown Assoc., Carson, CA., EPA Contract 68-02-2838, March, 1978.		
144	Gisser, P., "Benzene Emission Control Costs In Selected Segments of the Chemical Industry", Booz, Allen & Hamilton, Inc., Florham Park, N.J., Manufacturing Chemists Association, Washington, D.C., Rept. PB-283-781, June, 1978		
145	Anon., "Control of Volatile Organic Emissions From Existing Stationary Sources Volume I, Control Methods For Surface-Coating Operations", Rept. EPA-450/2-76-028 November, 1976.		

Source No.	Title	APTIC No.	NTIS No.
146	Perry, et al. "Chemical Engineers Handbook,		
147	Maxwell, J. B., "Data Book on Hydrocarbons", Standard Oil Development Company.		
148	Anon., "Cost Estimates of Upgrading Particulate Matter Controls on Copper Smelter Reverberatory Furnaces", Industrial Gas Cleaning Institute, Stamford, Conn., EPA Contract 68-02-2532, March, 1977.		
149	Cost Engineer's Notebook, American Association of Cost Engineers.		
150	C. H. Chilton, "Cost Engineering in the Process Industries", McGraw-Hill, 1960.		
151	Anon, "Industrial Ventilation" 10th Edition, American Conference of Governmental Industrial Hygienist.		
152	Hemeon, W.C.L., "Plant and Process Ventilation", Second Edition, The Industrial Press, New York, N.Y.		
153	Loyal Clarke, "Manual for Process Engineering Calculations", McGraw-Hill, 1947		
154	Anon, "Air Pollution Manual" PartII Control Equipment, American Industrial Hygiene Association.		
155	Strauss W. "Industrial Gas Cleaning" Pergamon Press, Second Edition 1975.		
156	Bauman, H.C. "Fundamentals of Cost Engineering in the Chemical Industry" Reinhold 1965		
157	Gaylord "Structural Engineering Handbook: McGraw Hill 1968.		
158	Anon, "Capital Costs of Free Standing Stacks" Vulcan - Cincinnatti Inc, EPA Contact #68-02-0299		
159	Holland, F.A., et al., "How to Estimate Capital Costs", Chemical Engineering, April 1, 1974.		
160	GARD in-house data.		

		APTIC No.	NTIS No.
161	Shaw, N.R., "Carbon Absorption/Emission Control Benefits and Limitations", Paper presented at symposium on Volatile Organic Compound Control in Surface Coating Industries, April 25-26, 1979 Chicago, Ill.		
162	Anon "Hydrocarbon Pollutant Systems Study" MSA Research Corp., EPA contract EHSD 71-72, January 1973.		
163	Private communication with PGST Company and vendor quote.		
164	Norman, W.S., "Absorption Distillation and Cooling Towers". Wiley Press., New York, N.Y. 1961		
165	Miller, J.S. et. al., "Cost of a Distillation Column" Chemical Engineering, April 11, 1977		
166	Pikulik, A., et. al., "Cost Estimating for Major Process Equipment" Chemical Engr, Oct. 10, 1977		
167	Steenberg, L.R. "Air Pollution Control Technology and Costs, Seven Selected Emission Sources". EPA-450/3-74-060, Dec. 1974		
168	White, H. J.; "Industrial Electostatic Precipitation", Addison-Wesley Publishing Co., 1963.		
169	Horzella, T. I., "Selecting, Installing and Maintaining Cyclone Dust Collectors", Chemical Engineering, January 30, 1978.		
170	Anon., "Review and Comments on Report Entitled Capital and Operating Costs of Selected Air Pollution Control Systems", PEDCo Environmental, Inc., August, 1979.		
171	Anon., Building Construction Cost Data, 35th Annual Edition, Means, 1977.		
172	Based on discussions with T. Tarnok of Joy/ Western Precipitation Division.		

APPENDIX D

GUIDE TO ASSOCIATIONS FOR THE INDUSTRIES

ASSOCIATIONS

1.	Air Pollution Control Association 4400 Fifth Avenue Pittsburgh, Pennsylvania 15213	Lewis H. Rogers Executive Vice President 412/621-1100
2.	Brick Institute of America 1750 Old Meadow Road McLean, Virginia 22101	R. W. Otterson Executive Vice President 703/893-4010
3.	Refractories Institute (Brick) 1102 One Oliver Plaza Pittsburgh, Pennsylvania 15222	Bradford S. Tucker Executive Secretary 412/281-6787
4.	Refractories and Reactive Metals Association P. O. Box 2054 Princeton, New Jersey 08540	Kempton H. Roll Executive Director 609/799-3300
5.	American Boiler Manufactures Association Suite 317, AM Building 1500 Wilson Boulevard Arlington, Virginia 22209	W. B. Marx Executive Director 703/522-7298
6.	National Grain and Feed Association 501 Folger Building Washington, D. C. 20005	Alvin E. Oliver Executive Vice President 202/783-2024
7.	Grain Elevator and Processing Society 2144 Board of Trade Building Chicago, Illinois 60604	Dean M. Clark Secretary-Treasurer 312/922-3111
8.	American Feed Manufactures Association 1701 N. Fort Myer Drive Arlington, Virginia 22209	Oakley M. Ray President 703/524-0810
9.	Midwest Feed Manufacturers Association 521 E. 63rd Street Kansas City, Missouri 64110	Rex Parsons Executive Vice President 816/444-6240
10.	American Glassware Association c/o Organized Service Corp. Managers One Stone Place Bronxville, New York 10708	Donald V. Reed Managing Director 914/779-9602

11. Associated Glass and Pottery Manufacturers
c/o Harold L. Hayes
Brush Pottery Company
P. O. Box 2576
Zanesville, Ohio 43701

Harold L. Hayes
Secretary
614/454-1216

12. National Association of Manufacturers of Pressed and Blown Glassware
c/o John H. Morris
707 Winmar Place
Westerville, Ohio 43081

13. Sealed Insulating Glass Manufactures Association
202 S. Cook Street
Barrington, Illinois 60010

Warren W. Findling
Executive Vice President
312/381-8989

14. Gray and Ductile Iron Founders' Society
Cast Metals Federation Building
20611 Center Ridge Road
Rocky River, Ohio 44116

Donald H. Workman
Executive Vice President
216/333-9600

15. Malleable Founder's Society
20611 Center Ridge Road
Cast Metals Building
Rocky River, Ohio 44116

Lowell D. Ryan
Executive Vice President

16. Non-Ferrous Founder's Society
21010 Center Ridge Road
Cleveland, Ohio 44116

Benjamin J. Imburgia
Executive Secretary
216/333-2072

17. Steel Founder's Society of America
20611 Center Ridge Road
Cast Metals Federation Building
Rocky River, Ohio 44116

Jack McNaughton
Executive Vice President
216/333-9600

18. Foundry Equipment Manufacturers Association
1000 Vermont Avenue
Washington, D. C. 20005

Charles E. Perry
Executive Secretary
202/628-4634

19. American Iron and Steel Institute
150 East 42nd Street
New York, New York 10017

John P. Roche
President
212/697-5900

20.	Ductile Iron Society P. O. Box 22058 Cleveland, Ohio 44122	James H. Lansing Executive Director 216/752-0521
21.	Roll Manufacturers Institute 1808 Investment Building Fourth Avenue Pittsburgh, Pennsylvania 15222	A. G. Karp Executive Secretary-Treasurer 412/281-0908
22.	National Council of the Paper Industry for Air and Stream Improvement 260 Madison Avenue New York, New York 10016	Ernest J. Bolduc, Jr. Executive Director
23.	American Paper Institute 260 Madison Avenue New York, New York 10016	Albert S. Thomas Secretary-Streasurer 212/889-6200
24.	Paper Industry Management Association 2570 Devon Avenue Des Plaines, Illinois 60018	H. Mac Gregor Tuttle Executive Director 312/774-6797
25.	Technical Association of the Pulp and Paper Industry One Dunwoody Park Atlanta, Georgia 30341	Phillip E. Nethercut Executive Secretary-Treasurer 404/457-6352
26.	National Lime Association 5010 Wisconsin Avenue, N.W., Washington, D.C. 20016	Robert S. Boynton Executive Director 202/966-3418
27.	National Crushed Stone Association 1415 Elliot Place, N.W. Washington, D.C. 20007	W. L. Carter President 202/333-1536
28.	Portland Cement Association Old Orchard Road Skokie, Illinois 60076	Robert D. MacLean President 312/966-6200
29.	Fertilizer Industry Round Table Glenn Arm, Maryland 21057	Paul J. Prosser Secretary-Treasurer 301/592-6271
30.	The Fertilizer Institute 1015 18th St. N.W. Washington, D.C. 20036	Edwin M. Wheeler President 202/466-2700

31.	Eastern States Blast Furnace and Coke Oven Association c/o Paul F. Ross Bethlehem Steel Corporation Johnstown, Pa. 15907	
32.	National Coal Association 1130 17th St. N.W. Washington, D.C. 20036	Carl E. Bagge President 202/628-4322
33.	Soap and Detergent Association 475 Park Avenue South New York, New York 10016	Theodore E. Brenner President 212/725-1262
34.	Manufacturing Chemists Association 1825 Connecticut Avenue, N.W. Washington, D.C. 20009	William T. Driver President 202/483-6126
35.	American Petroleum Institute 1801 K Street, N.W. Washington, D.C. 20006	Frank N. Ikard President 202/833-5600
36.	Coordinating Research Council 30 Rockefeller Plaza New York, New York 10020	M. K. McLeod, Manager 212/757-1295
37.	Independant Refiners Association of America 1801 K Street, N.W., Suite 1101 Washington, D.C. 20006	Edwin Jason Dryer General Counsel 202/466-2340
38.	National Petroleum Refiners Association 1725 De Sales Street, N.W. Suite 802 Washington, D.C. 20036	Donald C. O'Hara Executive Vice President 202/638-3722
39.	Western Oil and Gas Association 602 S. Grand Avenue Los Angeles, California 90017	Harry Morrison Vice President 213/624-6386
40.	Copper Development Association 405 Lexington Avenue 57th Floor New York, New York 10017	George M. Hartley President 212/867-6500
41.	Copper Institute 50 Broadway New York, New York 10004	H. Fasting Secretary 212/944-1870

42. Aluminum Association 750 Third Avenue New York, New York 10017	S. L. Goldsmith, Jr. Executive Vice President 212/972-1800
43. Incinerator Institute of America 2425 Wilson Blvd. Arlington, Virginia 22201	Charles N. Sumwalt, Jr. Executive Director 703/528-0663
44. American Public Works Association 1313 East 60th Street Chicago, Illinois 60637	Robert D. Bugher Executive Director 312/324-3400
45. National Solid Wastes Management Association 1730 Rhode Island Avenue, N.W. Suite 800 Washington, D.C. 20036	
46. Conference of State Sanitary Engineers Statehouse Charleston, West Virginia 25305	304/348-2970
47. American Society of Sanitary Engineering 960 Illuminating Building Cleveland, Ohio 44113	Sanford Schwartz Secretary 216/696-3228
48. National Cotton Ginner's Association Box 120 Maypearl, Texas 76064	Peary Wilemon Secretary-Treasurer 214-435-2741
49. The Cotton Foundation 1918 North Parkway Memphis, Tennessee 38112	George S. Buck, Jr. Executive Vice President
50. Cotton Incorporated 1370 Avenue of the America's New York, New York 10019	J. Dukes Wooters, Jr. President 212/586-1070
51. National Cotton Council of America 1918 North Parkway Memphis, Tennessee 38112	Albert B. Russell Executive Vice President and Secretary 901/276-2783

APPENDIX E

CONVERSION FACTORS TO SI MEASUREMENTS

APPENDIX E

CONVERSION FACTORS TO SI MEASUREMENTS

For a complete description of conversion factors to the International System of Units (SI), the reader is referred to the "Metric Practice Guide," American Society for Testing and Materials, pub. #E 380-72, approved by the American National Standards Institute, Std. #Z210.1-1973. The following are selected conversion factors that will accomodate all units found in this document, as well as other pertinent units. They are arranged alphabetically.

To convert from	to	Multiply by
atmosphere (normal=760 torr)	pascal (Pa)	$1.01325 * 10^5$
British thermal unit [+](Btu)	joule (J)	$1.05506 * 10^3$
Btu/ft^2	joule/metre^2 (J/m^2)	$1.13565 * 10^4$
Btu/hour	watt (W)	0.29307
Btu/pound-mass	joule/kilogram- (J/kg)	$2.326 * 10^3$
Btu/lbm·deg F (heat capacity)	joule/kilogram-kelvin (J/kg·K)	$4.18680 * 10^3$
Btu/s·ft^2·deg F	watt/metre^2-kelvin (W/m^2·K)	$2.04418 * 10^4$
calorie (International Table)	joule (J)	4.18680
day	second (s)	$8.64000 * 10^4$
degree Celsius (C)	kelvin (k)	$t_k = t_c + 273.15$
degree Fahrenheit (F)	degree Celsius	$t_c = (t_f - 32)/1.8$
degree Fahrenheit (F)	kelvin (k)	$t_k = (t_f + 459.67)/1.8$
foot (ft)	metre (m)	0.30480
foot^2 (ft^2)	metre^2 (m^2)	$9.29030 * 10^{-2}$
foot^3 (ft^3)	metre^3 (m^3)	$2.83168 * 10^{-2}$
foot/hour (fph)	metre/second (m/s)	$8.46667 * 10^{-5}$

[+] The Btu quantity used herein is that based on the International Table.

To convert from	to	Multiply by
foot/minute (fpm)	metre/second (m/s)	$5.08000 * 10^{-3}$
foot/second (fps)	metre/second (m/s)	0.30480
foot^3/minute (cfm)	metre^3/second (m^3/s)	$4.71947 * 10^{-4}$
foot^3/second (cfs)	metre^3/second (m^3/s)	$2.83168 * 10^{-2}$
gallon (U.S. liquid) (gal)	metre^3 (m^3)	$3.78541 * 10^{-3}$
gallon (U.S. liquid)/day (gpd)	metre^3/second (m^3/s)	$4.38126 * 10^{-8}$
gallon (U.S. liquid)/minute (gpm)	metre^3/second (m^3/s)	$6.30902 * 10^{-5}$
grain (gr)	kilogram(kg)	$6.47989 * 10^{-5}$
horsepower (hp)	watt (w)	$7.46000 * 10^{2}$
hour (hr)	second(s)	$3.60000 * 10^{3}$
inch (in)	metre (m)	$2.54000 * 10^{-2}$
inch^2 (in^2)	metre^2 (m^2)	$6.45160 * 10^{-4}$
inch of water (60F)	pascal (Pa)	$2.4884 * 10^{2}$
kilowatt-hour (kwh)	joule (J)	$3.60000 * 10^{6}$
minute (min)	second (s)	60.000
parts per million (ppm)	milligram/metre^3 (mg/m^3)	(molecular weight)/24.5
pound-force (lbf avoirdupois)	newton (N)	4.44822
pound-force/inch^2 (psi)	pascal (Pa)	$6.89476 * 10^{3}$
pound-mass (lbm avoirdupois)	kilogram (kg)	0.453592
pound-mass/foot^3 (lbm/ft^3)	kilogram/metre^3 (kg/m^3)	$1.60185 * 10^{1}$
pound-mass/minute (lbm/min)	kilogram/second (kg/s)	$7.55987 * 10^{-3}$
pound-mass/second (lbm/sec)	kilogram/second (kg/s)	$4.53592 * 10^{-1}$
ton (cooling capacity)	Btu/hr	$1.2000 * 10^{4}$
ton (short, 2000 lbm)	kilogram (kg)	$9.07185 * 10^{2}$